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Patterns of recent charcoal accumulation in sediments of a glacial lake in the páramo of Parque Nacional Chirripó, Costa Rica

Brandon L. League

To the Graduate Council:

I am submitting herewith a thesis written by Brandon L. League entitled "Patterns of recent charcoal accumulation in sediments of a glacial lake in the páramo of Parque Nacional Chirripó, Costa Rica." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Sally Horn, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Patterns of recent charcoal accumulation in sediments of a glacial lake in the páramo of Parque Nacional Chirripó, Costa Rica

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Abstract

The development of fire histories from sedimentary charcoal analysis requires an interpretation of the charcoal stratigraphy. This interpretation can be improved with knowledge of recent patterns of charcoal accumulation in the basins under study. To improve reconstructions of páramo fire history from glacial lake sediments in Costa Rica, I retrieved a series of short sediment cores from a glacial lake where previous studies confirmed repeated watershed fires at intervals throughout the Holocene. The cores were taken along a transect that crossed the lake, including the deepest point, and were sampled at contiguous 1-cm intervals. Analysis of these cores revealed the pattern of charcoal accumulation in the lake sediments following recent fire events. A comparison of different macroscopic size classes of charcoal particles indicates little difference in the pattern between size classes. The results suggest that wind-generated currents and fluvial deposition strongly influence the pattern of charcoal accumulation along the transect. Sediment accumulation rates were estimated based on a radiocarbon date, and used to construct charcoal influx diagrams. The temporal resolution of the charcoal record was estimated by interpreting the charcoal influx diagrams.

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Introduction

Fire history studies can be an effective way to learn about a wide range of issues that concern geographers. Vegetation fires occur when and where there is fuel, dry weather, and an ignition source. These ingredients in a fire event each point to conditions caused by a combination of climate, ecological processes, and human interaction with the environment. The frequency of fire events over time may provide information about trends or changes in climatic conditions, vegetation, and human population sizes and activities.

Analysis of charcoal concentrations in lake sediments can yield valuable information for the development of regional and local (*i.e.*, watershed) fire histories. Studies of sedimentary charcoal in the Chirripó páramo of Costa Rica have shown that fires have burned in the páramo repeatedly since the area was deglaciated approximately 10,000 ^{14}C yr BP (Hom, 1993; League, 1998; League and Hom, 2000; Orvis and Horn, 2000). Further study of charcoal or other proxy evidence is necessary to establish characteristics of the fire regime such as frequency, intensity, and area burned. The massive (non-laminated) nature of the sediments in glacial lakes of the Chirripó páramo makes it difficult or impossible to determine all of these characteristics based on sedimentary charcoal. However, existing fire history reconstructions can be improved through investigation of taphonomic processes affecting modem charcoal accumulation in the lakes.

From Lago Morrenas 1 in the Chirripó páramo, I collected a series of short sediment cores that preserve the uppermost sediments, including the sediment-water interface. The pattern of charcoal concentration in these recent profiles provides clues about the workings of physical processes such as sediment focusing, postfire fluvial deposition, and movement of sediments from wave action, wind-driven currents, and bioturbation. These clues, along with a comparison of the charcoal concentration patterns to historical information about recent fire events, can provide guidelines for interpreting the longer-term fire history of the Chirripó páramo from charcoal in older sediments (League, 1998; League and Horn, 2000).

This thesis is divided into five chapters. Chapter One reviews the literature concerning fire history studies based on sedimentary charcoal. In Chapter Two, I describe the environmental setting of my study site, located in the Chirripó páramo of Costa Rica. Chapter Three describes the methods I used for fieldwork and laboratory analysis. Chapter Four presents the results of my study. Chapter Five discusses the results, and is followed by the conclusion.

1.0 Fire History and Sedimentary Charcoal

1.1 Introduction

Methods for learning about fire history include the study of charcoal in lake sediments. This technique provides evidence of fire that can be placed into a chronological and spatial framework, but each study can vary in spatial resolution, temporal resolution, and temporal extent, depending on the specific methodology, research design, and site conditions. In this chapter, I will describe fire history research based on sedimentary charcoal, and I will discuss issues relating to methods and interpretation of data.

1.2 Historical Development of Charcoal Studies

Fire history research based on sedimentary charcoal began as a complement to investigations of past vegetation based on analysis of pollen in bog and lake sediments. Iversen (1941) noticed charcoal on microscope slides that were prepared for pollen analysis and recognized an opportunity to learn about the relationship between fire and vegetation over time by interpreting periods of greater fire frequency from relatively high quantities of charcoal in sediments. This technique was adopted by many paleoecologists doing pollen analysis, and was reviewed by Patterson *et al.* (1987).

The practice of developing fire histories based on sedimentary charcoal as a corollary to pollen investigations subjects charcoal fragments to the same procedures that are used for making microscope slides for pollen analysis. R. Clark (1984) examined how pollen slide preparation techniques affect charcoal particles and found that the procedures commonly used for preparing microscope slides could cause charcoal particles to break into smaller pieces, and could cause some particles to be destroyed completely. Slide preparation procedures vary according to the type of sediment, and a variety of procedures may be used on sediments from the same core. When these procedures affect charcoal in different ways, and to varying degrees, interpretation of fire history from the sedimentary charcoal can be problematic (R. Clark, 1984).

Even so, over 70% of all paleoecological studies that include charcoal data use pollen preparation techniques to quantify the charcoal (Rhodes, 1998).

J. Clark contributed to the science of fire history studies based on sedimentary charcoal records by critiquing the theoretical framework and methodology that had become commonplace (Clark, 1988). He addressed the issues of temporal and spatial scale in fire history research based on sedimentary charcoal. He also developed a new technique for studying fire history based on macroscopic charcoal, and a theoretical framework for interpreting charcoal data.

The formation of charcoal during a fire event, and the subsequent deposition on the water surface of a lake, can be compared to the production, transport, and deposition of pollen, and is the basis for applying theories of pollen transport and deposition to the interpretation of charcoal stratigraphy (Patterson *et al.,* 1987). However, J. Clark (1988) described how theories of particle motion apply to the production, transport, and deposition of charcoal during and after a fire event, and he pointed out that the differences between pollen and charcoal must be taken into account.

The major difference between the use of pollen and charcoal as paleoenvironmental proxies is related to temporal interpretation. Charcoal peaks can be used to identify the occurrence of a wildfire in the past. Such fires are events that occur at a discrete moment in time, whereas pollen records are used to identify trends that occur over long periods of time. A variety of taphonomic processes act on particles of both pollen and charcoal that may cause them to be distributed through a section of core that corresponds to a time interval of many years. This is problematic for the interpretation of charcoal stratigraphy, because the fire event occurs in a discrete moment in time.

Another important difference between the use of pollen and charcoal as proxies is related to spatial interpretation. The identification of a source area for pollen and charcoal is an important part of paleoecological studies. Differences between the motion of pollen and charcoal particles as they are transported and deposited require that they be interpreted differently. Clark's (1988) work on applying theories of particle motion to charcoal particles was primarily related to this aspect of charcoal interpretation.

Clark (1988) applied particle motion theories to charcoal particles to develop a conceptual framework for the movement of charcoal from the point of production to its deposition from aerial fallout to the water surface of a lake. In order to simplify his model, he used terminology referring to windbome particles in a specific way that separates the processes of saltation and traction from the process where charcoal is lifted into the air by a heat plume, and subsequently moved by wind. He described the latter process in detail, arguing that the size of the charcoal particle, the height of the heat plume created by a fire, and the wind speeds during the fire are the most important variables affecting the distance that charcoal is moved away from the fire location.

According to Clark's (1988) model, sand-sized (60–2000 µm) charcoal particles moved by aeolian saltation and traction are more likely to travel short distances (less than 1 km) along the ground surface at normal surface wind speeds. Particles less than 60 µm could be entrained by the wind at the ground surface and moved distances greater than 1 km, but sand-sized particles must be lifted to heights by the convection produced by a fire in order to be moved greater distances by wind. Clark distinguished these size classes by referring to charcoal less than 60 µm as microscopic, and particles greater than 60 µm as macroscopic.

Based on these assumptions, Clark (1988) described the charcoal transport distance expected of macroscopic charcoal with various combinations of particle size, heat plume height, and wind speed. His description relies on the assumption from particle motion theory that macroscopic charcoal particles fall out at predictable distances from the point of entrainment according to particle size. Clark argued that macroscopic charcoal would fall out quickly and would be deposited locally, so that macroscopic charcoal in lake sediments would be evidence of a fire event in the immediate vicinity of the lake.

Clark (1988) also pointed out that a large component of charcoal preserved in lake sediments is deposited after the fire event. The source of this charcoal is the particles that were deposited on the land surface during the fire event. These charcoal particles can be transported into the lake by both aeolian and fluvial processes. This is commonly referred to as secondary input, whereas deposition from airborne fallout is primary input. Secondary input also includes charcoal that is reworked by various mechanisms within the lake and redeposited (Clark, 1998; Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996; Gardner and Whitlock, 2001). A proper temporal interpretation of the stratigraphic charcoal record requires careful consideration of the importance of this component of the charcoal preserved in the lake sediments.

Clark (1990) also tested these theories with case studies. In one example, he compared the charcoal records of three nearby lakes. These charcoal records were developed using a thin-section technique for counting macroscopic charcoal in varved sediments. Thus, these fire-history records were based on large fragments that likely originated from nearby fires, and had a tight, annual chronological control. Differences between the charcoal records led Clark to conclude that each lake recorded a different, local fire history.

1.3 Taphonomlc Processes

Several post-depositional processes can affect the way that charcoal is distributed in lake sediments. Sediment and charcoal particles can be moved both vertically and horizontally after initial deposition (Larsen and MacDonald, 1993). Horizontal movement of sediment and/or charcoal particles can be caused by sediment slumping, waves, or currents (Larsen and MacDonald, 1993), or by changes in water level that expose near-shore sediments to additional erosion processes (Hom and Sanford, 1992). Horizontal movement of sediment within lakes that results in a net movement from shallow water to deep water is referred to as sediment focusing. Any or all of the previously mentioned processes that cause post-depositional, horizontal movement of sediments can cause sediment focusing, which results in a stratigraphic pattern in which older sediments are found at greater depth in the center of the lake (Larsen and MacDonald, 1993).

Vertical movement of sediment and charcoal, which can also be referred to as sediment mixing, is generally the result of bioturbation. Bioturbation can be caused by benthic organisms that can possibly live as much as 25 cm below the sediment-water interface (Davis, 1974), and has been reported to integrate sediment layers by as much as 60 years (Robbins, 1982). These organisms rework sediments by moving more deeply buried sediments toward the surface while younger sediments closer to the surface are mixed downward. In stratified lakes in which anoxic conditions develop below the thermocline, bioturbation is generally thought to be limited. However, research has also shown that some benthic organisms can survive for up to one month under anoxic conditions (Larsen and MacDonald, 1993). Davis (1974) focused on the problem of organisms feeding on pollen grains and transporting them in their feces to different depths below the sediment-water interface. Bioturbation may, therefore, be more problematic for pollen studies than for charcoal studies. It is also plausible that larger organisms, including tapirs in páramo lakes, can thrash about and disturb sediment layers (S. Horn, pers. comm.).

Larsen and MacDonald (1993) reviewed the literature concerning sediment mixing and described how basic morphometric characteristics could be used to predict the likelihood of sediment mixing in a lake. They described the factors that cause sediment mixing in small lakes of the type usually selected for paleoenvironmental studies. These factors include mixing caused by (1) gravity induced sediment slumping, (2) wave action, (3) currents, and (4) bioturbation.

Subaqueous sediment slumping is caused by gravity and its occurrence is related to slope angle and sediment stability. Sediment stability is primarily a function of particle size and water content. Slumping has been reported at a lake in Canada on slopes of 5° with fine-grained sediments (Bennett, 1986). Ludlam (1974) found that 50% of the matter in the center of a steeply sloped lake originated from slumping, and that turbidite flows can extend as far as 170 m from the point of slumping (Larsen and MacDonald, 1993).

A wave is a periodic motion of water caused by wind, whose size is determined by wind speed, lake fetch, and water depth. Waves always disturb sediments in the littoral zone, but in shallow lakes, waves can disturb the sediments in the center of a lake. For example, a wind speed of 18 cm/s with a lake fetch of 200 m will create orbital motion of water that reaches 2–3 m deep (Larsen and MacDonald, 1993).

A current is a non-periodic motion of water caused by wind, temperature differences in the water column, or fluvial input (Larsen and MacDonald, 1993). Wind-generated currents consist of a surface flow with a speed that is generally 2% of the wind speed, although this ratio is highly variable (Wetzel, 1983). Return flow occurs at depth or in the form of a longshore current at the surface. The return flow at depth may move along the thermocline in a stratified lake, or the lake bottom in unstratified lakes. Hellström (1941) suggested that his calculations indicate that the speed of the return flow is 30% of the speed of the surface flow. Larsen and McDonald (1993) described an example in which a 100 km/hr wind would generate a return flow along the lake bottom of 16.7 cm/sec. This is enough to entrain fine sediments, but since the presence of a thermocline would usually protect the lake bottom from currents (Mortimer, 1952), an example such as this would only cause significant sediment mixing in an unstratified lake (Larsen and MacDonald, 1993).

Larsen and MacDonald (1993) compiled a database of lakes that included information about lake morphometry, sediment type (laminated or massive) and water column mixing. They showed how basic information about surface area and maximum water depth can be used to predict whether or not the lake will posses annually laminated sediments. They found that surface area and depth could be used to develop a heuristic for predicting whether a lake is dimictic, meromictic, or polymictic. This categorization is useful for determining sediment type, and for predicting the processes that cause sediment mixing (Larsen and MacDonald, 1993).

Hilton (1985) also described the relationship between lake morphology and sediment mixing. This work was based on data from sediment traps, and was used to predict the occurrence of each of the processes that cause sediment redistribution.

Annually varved sediments are ideal for macroscopic charcoal analysis because they provide a tight chronological control on the sediment age and allow the researcher to interpret discrete fire events (Clark, 1990), much like studying fire scars on trees with annual growth rings. Many lakes that are located in areas where researchers are interested in the fire history do not have annually laminated sediments. The most interesting questions concerning fire are often in places where conditions for basing fire history on sedimentary charcoal are not ideal.

Refinement of technique for basing fire history on sedimentary charcoal studies may improve what can be learned from studies at sites that lack annually varved sediments. Earlier studies done in conjunction with pollen analysis often used a sampling strategy that was determined by the needs of the paleovegetation study. This resulted in a wide interval sampling procedure that could miss entire fire events. Studies by Millspaugh and Whitlock (1995) and League and Horn (2000) improved on this by sampling for charcoal at contiguous intervals. Other researchers (Long *et al.*, 1998; Gardner and Whitlock, 2001) have further attempted to solve the problem of temporal resolution in charcoal studies in profiles of massive lake sediments by developing chronologies with ^{210}Pb analysis, which is useful for dating sediments less than 500 years old, and by defining charcoal peaks with statistical analyses.

J.P. Bradbury (1996) asserted that lacustrine redeposition of charcoal must be evaluated before sedimentary charcoal records can be related to fire events at any scale. Bradbury based this assertion on the study of microscopic charcoal in sediment traps and a transect of surface samples from Elk Lake, Minnesota. This study provided qualitative information that was used to make inferences about the mechanisms by which previously deposited charcoal is redeposited within the lake.

Bradbury related this charcoal data to information about diatoms and phytoliths, and concluded that the redeposition of charcoal was caused by seasonal circulation events. The last fire in the watershed of Elk Lake occurred in 1922, but the sediment trap collected charcoal at a rate of 1–2 fragments/10 mm traverse across a microscope slide. Bradbury attributed this to a combination of a possible background level of regional wind-borne charcoal and lacustrine redeposition. Charcoal peaks developed over an average 5 yr period when, during seasonal turnover, charcoal deposits in the littoral zone were entrained and re-deposited in the profundal region of the lake.

1.4 Recent Studies of Macroscopic Charcoal

Paleoecologists continue to use microscopic charcoal data from pollen slides to complement their paleovegetation studies, but a number of fire history researchers utilizing sedimentary charcoal have limited their studies to the use of macroscopic charcoal data. Millspaugh and Whitlock (1995) developed a wet-sieving technique for quantifying and analyzing macroscopic charcoal. Whitlock and other collaborators have utilized this technique in a series of studies (Whitlock and Millspaugh, 1996; Long *et al.*, 1998; Gardner and Whitlock, 2001), and other researchers have adopted the method as well (League and Hom, 2000). One advantage of this method is that it ensures that the charcoal fragments that are used as proxy evidence of fire events were produced largely by locally occurring fires. This technique also does not require any complicated processing with dangerous chemicals.

A group of recent studies of charcoal sedimentation following known fire events are widely cited and provide examples of how to develop fire histories based on macroscopic sedimentary charcoal. Millspaugh and Whitlock (1995), and Whitlock and Millspaugh (1996) studied post-fire deposition of charcoal in lakes in Yellowstone National Park after the 1988 fires, and Clark et al. (1998) studied postfire charcoal sedimentation after a prescribed burn in Siberia. In addition, Gardner and Whitlock (2001) studied postfire charcoal sedimentation in lakes in Oregon after a fire in 1996, and Blackford (2000) examined charcoal fragments in surface samples of heathland sediments in England following a fire.

Millspaugh and Whitlock (1995) used the macroscopic charcoal wet-sieving technique to develop a 750-year fire history from lake sediment profiles in central Yellowstone National Park. Their objective was to develop a fire history, and determine the degree of spatial and temporal resolution that could be obtained by combining multiple lines of proxy evidence at well-chosen sites.

Millspaugh and Whitlock (1995) compared the charcoal record of a large lake (4250 ha) with the charcoal records of several nearby small lakes (<19 ha) to distinguish between local and regional fires. Some of these lakes were located within burned areas, while others were located in unburned areas. They defined local fires as those that occur within the watershed of a lake. By comparing the charcoal stratigraphy of lakes in burned and unburned areas, they determined whether or not the fire was represented by a peak of charcoal in the uppermost lake sediments. They used evidence of fire-related erosion to distinguish between local and extra-local fires.

Whitlock and Millspaugh (1996) examined the charcoal stratigraphy of a series of cores from each of eight lakes that are located in or near areas burned by the 1988 Yellowstone fires. This technique made it possible to determine the spatial and temporal variability of charcoal within the lakes as well as between sites. At each study site, they collected a series of sediment cores along a transect from shallow to deep water. Contiguous 1 cm samples were wet sieved through a nested series of metal screens, and the charcoal particles were counted under a stereomicroscope. The ages of the sediments were determined by ^{210}Pb analysis, and charcoal accumulation rates were plotted against the age of the core. They also measured the magnetic susceptibility of the sediment samples and compared all of these data with fire histories developed from studies of tree rings and stand age classes.

Charcoal peaks were matched with a known fire event, the 1988 fire that burned much of the forest in Yellowstone National Park, as well as with fires documented in the dendrochronological record. Whitlock and Millspaugh (1996) assumed the level of charcoal accumulation in non-fire years to be the background level of charcoal. The source of this charcoal includes wind-transported charcoal from distant, regional fires (Patterson *et al.*, 1987), and residual charcoal from previous local fires. The comparison of the pattern of charcoal peaks with the dendrochronological record justified an extension of the sediment-based fire history beyond the period recorded by tree rings.

Millspaugh and Whitlock (1995) found that information about the local and regional importance of fire histories could be determined from studies of lake sediments when the fire history study also utilizes additional proxy data. The fire history must be calibrated with known fire events for interpretation. Millspaugh and Whitlock (1995) also found that magnetic susceptibility measurements were useful in discriminating between local and extra-local fires.

Postfire mass wasting is common at their study sites, and the deep and cone-shaped bathymetry of the lakes is believed to be ideal for focusing sediments.

At sites without these characteristics, such as Morrenas Lake 1, it is less likely that magnetic susceptibility measurements can be used as evidence of local fires (League, 1998). The organic, autogenic material in lake sediments has very low magnetic susceptibility, whereas the mineral matter introduced into lake sediments by postfire mass wasting has higher magnetic susceptibility. Sites where postfire mass wasting and sediment focusing are not common are unlikely to have spikes in magnetic susceptibility in the sediment stratigraphy.

Whitlock and Millspaugh (1996) noted that fire history studies that utilize sedimentary charcoal as proxy evidence of fire rely on several assumptions. They tested these assumptions by examining modern charcoal sedimentation in a group of lakes in Yellowstone National Park. The assumptions they tested are (1) that charcoal peaks indicate a fire event, (2) that the source of sedimentary charcoal is primary fallout during or shortly after a fire, and (3) that large particles indicate local fires. Other common assumptions in charcoal-based fire history studies are that charcoal stratigraphy is similar throughout a lake, and that small lakes record local fire better than large lakes (Whitlock and Millspaugh, 1996).

Whitlock and Millspaugh (1996) focused the discussion of their results on the five most common assumptions in fire history studies. Perhaps the most important of these is whether or not charcoal peaks indicate a fire event. Their results indicate that charcoal continues to be deposited in the sediments after a fire, but they believe that with sediment compaction over time, the charcoal forms a distinct peak with a width determined by the length of time that charcoal continues to accumulate.

They also addressed whether or not fire proximity can be inferred from charcoal size. They examined several size classes of charcoal particles, and their results indicate that charcoal in all of these size classes was deposited in the sediments following the 1988 Yellowstone fires. Whitlock and Millspaugh (1996) found that four years after the Yellowstone fire, at the time of sample collection for their study, charcoal was still being deposited into the center of the lake basins.

Whitlock and Millspaugh (1996) found more charcoal in the littoral zones of the lakes than the deepwater areas. The sediments from the shallow water, downwind coring sites had the highest charcoal concentrations. Possible mechanisms for the transport of charcoal from shallow water to deep water are sediment slumping and movement of sediments by wind generated currents (Whitlock and Millspaugh, 1996).

They also described other ways that charcoal may have been transported into the lake sediments. They noted post-fire debris flows in two watersheds, although the material did not reach the lake shore. In three lakes in their study, charred trees fell into the lake, and charcoal from nearby charred trees was deposited onto the icy surface of lakes by wind during the winter, and later introduced to the lake sediments (Whitlock and Millspaugh, 1996).

Their results indicate that the deepest part of a lake is indeed the best place to retrieve a sediment core. The stratigraphy at their deep water coring sites showed a steadier pattern of accumulation than the littoral zones. In addition, sediments on the downwind side of the lakes had higher levels of charcoal concentration. This suggests that choosing coring sites on the upwind side of a lake could result in missed fire events, but more importantly, that the center of a lake is a better choice in order to minimize the influence of wind-generated currents.

Clark *et al.* (1998) conducted an experimental burn in Siberia to measure the charcoal produced by the burn, and to relate that information to fire characteristics, biomass burned, and charcoal in lake sediments. They collected samples from charcoal traps and lake sediment cores, quantifying both by sieving through 180, 250, and 500 µm mesh screens and counting on petri dishes. They also looked at pollen and microscopic charcoal in the lake sediments. Before and after the bum, they surveyed the amount of fuel in the burn area. This was done in order to estimate the burned biomass, and they related that figure to the amount of charcoal deposited in the traps. The charcoal traps were designed to simulate the surface of a lake, so that their data could be compared with and applied to charcoal data collected from lake sediments. They also collected detailed information about the characteristics of the fire, such as the fire intensity, wind direction, and height of the heat plume.

Most studies of atmospheric particle motion have been done on the motion of microscopic particulate matter. These microscopic particles are referred to as aerosols. Clark *et al.* (1998) found that the amount of macroscopic charcoal particle production from the experimental bum was much higher than studies of aerosols would suggest, because his measurements were taken at the ground surface, and aerosols are measured from samples taken from aircraft at high altitudes. This indicates that a large proportion of the charcoal produced in a fire settles out quickly and close to the source. This could also mean that secondary transport of charcoal is more important than expected (Clark *et al.*, 1998).

Clark *et al.* (1998) found that accumulation rates of charcoal in lake sediments were higher than those observed in traps. They offered several explanations for this, but they focused on the likelihood of secondary input. They cited previous studies (Clark and Royall, 1994; Clark *et al.*, 1996) in which sedimentary charcoal was higher than expected based on estimates of fuel loadings, burn efficiency, and emission factors, arguing that this trend supports the interpretation that fluvial transport and within-lake redeposition adds significantly to the charcoal transported by wind during a fire. They did suggest that secondary input could be balanced by the tendency of charcoal to accumulate in littoral zones, and they mentioned that more studies that focus on this aspect of sedimentary charcoal are necessary.

With regard to particle sizes, Clark *et al.* (1998) found similar patterns between all charcoal size classes in their Siberian study, but larger particles were more important when the source area was nearby. They concluded that past changes in charcoal accumulation at nearby Bor Lake could be the result of changes in fire frequency, changes in sedimentation patterns within the lake, or both.

Gardner and Whitlock (2001) examined the accumulation of charcoal in 29 lakes following a fire that occurred in 1996. Their study provided evidence that the fire event was registered by a peak in charcoal abundance. They also concluded that prevailing winds affect the transportation of macroscopic charcoal by increasing the charcoal abundance in lakes downwind of the fire. They suggested that the most important variables influencing charcoal abundance are those that are strongly related to the occurrence of sediment mixing: lake surface area and maximum water depth. Lake surface area is related to sediment mixing because wind speeds are higher with a greater fetch, and therefore wind driven currents are stronger. Maximum water depth is related to sediment mixing because in shallow lakes, the sediments are more likely to be disturbed by wind-driven currents.

Gardner and Whitlock (2001) employed the wet-sieving method for quantifying charcoal. They collected a short (12 cm) sediment core from each lake, and they sampled the uppermost sediments in those cores. They washed 5 cm^3 samples that were taken from contiguous, 2 cm slices of core, through nested 250 µm and 125 µm mesh screens, and counted charcoal fragments with a binocular microscope. They used regression analysis to determine the importance of a variety of factors influencing charcoal abundance. These variables include whether the area adjacent to the lake was burned or unburned, fire severity of burned areas, relative position (upwind or downwind), surface area, depth, maximum adjacent slope, extent of riparian margin, and the distance of the lake from the center of the fire.

Their results showed that the lakes located within burned areas received more charcoal than lakes in unburned areas. This is the main evidence that supports the assumption that fire events are registered by charcoal peaks. Lakes within unburned sites did, however, accumulate charcoal. Their study also showed that prevailing winds are capable of transporting enough charcoal in size ranges between 125 µm and 250 µm into unburned areas to create a charcoal peak in the lake sediments, although these peaks were significantly smaller than peaks in the lake sediments within burned areas.

Gardner and Whitlock (2001) concluded that surface area and maximum water depth were important due to the relationships between these morphometric characteristics and sediment mixing. Variables other than lake surface area, burn status, and fire severity were not significantly related to charcoal abundance. The authors concluded that additional studies to address the importance of secondary charcoal transport are necessary (Gardner and Whitlock, 2001).

Blackford (2000) also found differences in charcoal abundance between surface samples from burned and unburned sites. Blackford examined modern microscopic charcoal accumulation in terrestrial sediments following a heathland fire in England in 1997. This study focused on testing the assumption that fires are represented by charcoal peaks in a stratigraphic record. Blackford collected surface samples in plots, along a transect crossing burned and unburned areas, and along a transect across the woodland edge. The purpose of the transect across the woodland edge was to collect samples that would provide a comparison between charcoal in heathland soils and woodland soils. Samples were prepared with pollen preparation techniques and quantified on microscope slides with the point-count method (R. Clark, 1984).

Blackford (2000) found higher concentrations of charcoal in burned than in unburned areas. He also argued that the results indicated that most charcoal is derived from airborne fallout during a fire event. However, many of the taphonomic processes for secondary input that are at work in lake sediments are not in effect in terrestrial samples. Blackford found that large particles were more abundant in burned areas and less abundant or absent in unburned areas. He also found high variability in charcoal accumulation between closely spaced samples, although the contrast between burned and unburned sites could still be recognized. Blackford noted that post-depositional processes have not been studied and suggested that future research should address postfire redeposition.

All of these studies (Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996; Clark *et al.*, 1998; Gardner and Whitlock, 2001; Blackford, 2000) mentioned the possible importance of secondary input of charcoal from processes such as fluvial deposition and within-lake movement of sediments, but none of these studies focused primarily on determining the importance of secondary input.

Pitkänen *et al.* (1999) also confirmed that peaks in microscopic charcoal could be evidence of local fires at a study site in Sweden. This study combined an analysis of fire-scarred trees with an analysis of charcoal in lake sediments. The age of sediments with charcoal peaks in microscopic size classes matched the dates of fires determined from the dendrochronological evidence. This does not, however, rule out the possibility that microscopic charcoal peaks could be caused by regional fires.

MacDonald *et al.* (1991) assessed the use of several proxy indicators of fire that can be studied in lake sediments, including microscopic charcoal and fossil pollen, chemical digestion-combustion of charcoal, macroscopic charcoal, and sedimentological and geochemical data. They used each of these techniques to develop a fire history of a site in Wood Buffalo National Park, Alberta, Canada. They found that each type of proxy evidence produces different results, and none of the records matched exactly the known historical record of fire events.

According to Carcaillet *et al.* (2001), the most pressing questions regarding the use of sedimentary charcoal data to develop fire histories regard the minimum sediment sample size and the choice of size class of particles to study. They also brought up the issue of taphonomic processes such as within-lake sediment redeposition, bioturbation, disturbance from currents, and sedimentation of secondary charcoal. They did not examine taphonomic processes in their study, but they did an experiment to test the minimum volumetric sample size necessary for obtaining repeatable measurements of sedimentary charcoal. They also compared the method of wet-sieving macroscopic charcoal with the method of counting charcoal fragments on pollen slides. They relied on previous studies to choose the size class of particles to study.

Carcaillet *et al.* (2001) obtained multiple charcoal measurements for each level in a lake sediment core and found that, for their study site, a 1 cm^3 sample size was sufficiently large to obtain replicable charcoal measurements. They did find differences between the charcoal data that were obtained by counting charcoal on microscope slides, and by wet-sieving macroscopic charcoal. Their results suggested that macroscopic charcoal data provides information about local fire history, while the microscopic charcoal data provide information about regional fire history (Carcaillet *et al.*, 2001).

League and Horn (2000) analyzed a 5.6 m lake sediment core from Lago (Lake) Morrenas 1, in Chirripó National Park, Costa Rica, at contiguous 1-cm intervals for macroscopic charcoal. They concluded that the presence of macroscopic charcoal greater than 500 μm throughout the core demonstrated the occurrence of fire at repeated intervals throughout the Holocene. The close interval sampling allowed for the identification of charcoal peaks that had been missed by previous, wider interval sampling of microscopic charcoal on pollen slides (Horn, 1993). In conjunction with this study, they also tested the utility of magnetic susceptibility for identifying local fires (League, 1998). Higher levels of magnetic susceptibility corresponded to 1 cm sections containing fine sand, but these did not correspond to charcoal peaks.

Several researchers have performed statistical analysis on macroscopic charcoal curves to identify charcoal peaks that are significantly higher than the background levels, thus suggesting charcoal influx caused by a local fire event (Long *et al.*, 1998; Mohr *et al.*, 2000; Brunelle and Anderson, 2003). This technique of statistical analysis, using specialized software, requires the researcher to make assumptions about the temporal resolution of the charcoal record and the amount of charcoal that constitutes a background level. These assumptions can be made arbitrarily, or they can be based on characteristics of the study site and on an understanding of the lake system and the processes that influence the sedimentary charcoal record.

This thesis research on patterns of recent charcoal accumulation in Lago Morrenas 1 was developed to provide a stronger basis for interpreting the existing high resolution charcoal record (League and Horn, 2000) and others that are being developed from the glacial lakes of Cerro Chirripó.

2.0 Environmental Setting

2.1 Introduction

The site that I studied for this thesis is located in the Cordillera de Talamanca of Costa Rica. The highest peaks of this mountain range are located within Chirripó National Park. This park encompasses a diverse array of forest types, as well as páramo. The páramo is found above treeline at elevations from ~3400 m to 3819 m.

Páramo is a term that is used to describe the grass/shrub vegetation found above treeline in the neotropics, as well as the climate pattern that creates the conditions for this unique plant association. Páramo vegetation occurs in Ecuador, Colombia, Venezuela, and Costa Rica, but the most extensive areas of páramo are found in the Andes, and the term most often refers to this area (Luteyn, 1991). Páramos are found in a wide variety of environments, but common plant associations, or simply the lack of trees, define them. Páramo vegetation is noted for its high diversity, relative to other alpine vegetation types, and its high rate of endemism. Most páramos have a long history of human occupation, and are important for agriculture and water resources (Luteyn, 1991).

Human-set fires have affected many páramo areas in recent decades (Luteyn, 1991). Horn (1989, 1990a) has studied postfire vegetation dynamics in the Chirripó páramo, and Horn and League (Horn, 1993; League and Horn, 2000) have studied long-term fire history. In this chapter, I describe the climate, geology, and vegetation of the Chirripó páramo, as well as the role of fire in this environment, and its long term environmental history. Figure 2.1 shows the location of the Chirripó páramo within the Cordillera de Talamanca. My study site is a lake at the base of Cerro Chirripó.

2.2 Climate

Unique characteristics of high montane areas of the neotropics, such as the highest peaks of the Cordillera de Talamanca, produce climatic conditions that support páramo vegetation. These conditions, a function of the tropical latitude and high elevations, constitute

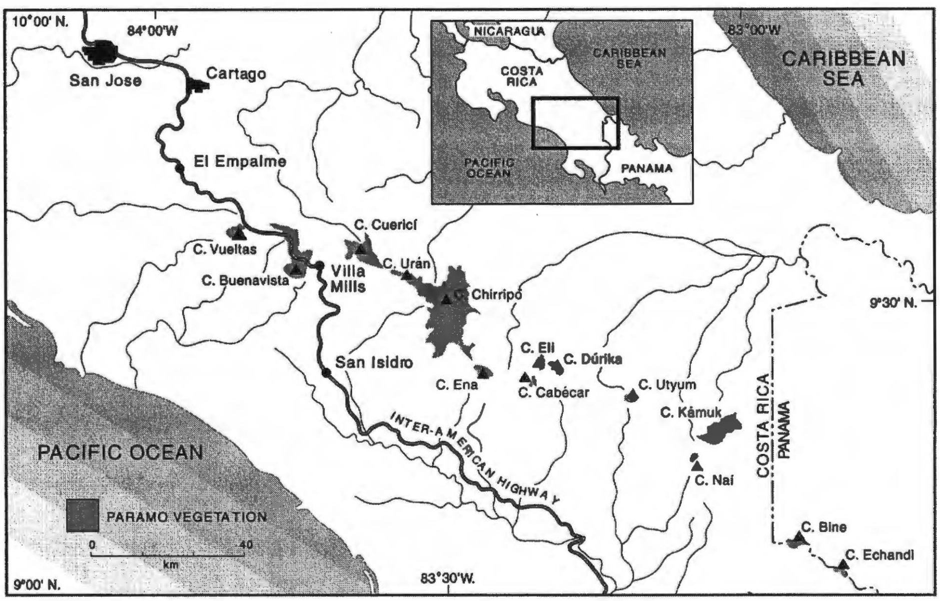

Figure 2.1 Areas of Páramo Vegetation in Costa Rica. From Horn (in press) with slight modifications.

what can be referred to as a "páramo" type climate. The diurnal fluctuation of temperature in the páramo is extreme, from less than 0°C to 23°C, and typically causes a freeze-and-thaw cycle. The annual precipitation, which is strongly seasonal, varies widely, from 500 mm to over 3000 mm (Luteyn, 1991).

Table 2.1 presents unpublished climate data from the Cerro Páramo meteorological station, located approximately 40 km northwest of Cerro Chirripó in the Buenavista páramo (Fig. 2.1). The data are probably broadly representative of conditions within the Chirripó páramo, from which only spotty, short-term data are presently available.

2.3 Geology

The Cordillera de Talamanca consists of an uplifted granodioritic batholith intruded into Tertiary marine basalts and sedimentary rocks. The Chirripó massif was deglaciated approximately 10,000 ^{14}C yr BP (Horn, 1990b; Orvis and Horn, 2000). The landscape today is a good example of alpine glacial geomorphology modified by high-elevation processes unique to tropical areas, such as high amounts of seasonal rainfall.

The Valle de las Morrenas contains a series of glacial lakes. Previous studies (Haberyan and Horn, 1999; Orvis and Horn, 2000) have referred to the lakes in the Valle de las Morrenas with a numeric system in which the lake that I studied is Lake 1. I follow this convention in this thesis. Lake 1 was previously described (Hastenrath, 1973) as moraine-dammed. Although there are moraines surrounding the lake, Orvis and Horn (2000) described the upper portion of the valley as a high-relief stoss-and-lee topography covered by glacial till, and they describe Lake 1 as a tarn carved into bedrock. Moraines, however, are located throughout the valley, and in some places do dam lakes. Orvis and Horn (2000) described other parts of the valley as having ice stagnation topography with small kettles. Hastenrath (1973) found humus to 25 cm depth in a soil pit dug near Morrenas Lake 1, with yellowish loam beneath. Orvis and Horn (2000) reported finding similar soils on tills in the upper part of the valley.

Table 2.1 Páramo Climate. Climate data representative of Costa Rican páramos from Cerro Páramo Meteorological Station, Cerro Buenavista massif, Costa Rica.

Month	Mean Precip.	Mean T Min	Mean T Mean	Mean T Max
January	41.0	3.1	7.9	12.5
February	31.3	3.4	8.3	13.3
March	34.0	3.7	9.1	14.3
April	105.0	4.4	9.4	14.1
May	354.1	5.0	9.1	13.4
June	330.3	4.8	8.9	13.0
July	226.0	4.2	8.2	12.4
August	344.6	4.3	8.3	12.5
September	409.4	4.5	8.3	12.4
October	408.8	4.4	8.2	12.2
November	212.6	4.2	8.1	12.0
December	83.9	3.5	7.8	11.9
Total	2581.1	4.1	8.5	12.8
D/JFMA	295.2	3.5	8.4	13.1
AMJJ	1015.5	4.6	8.9	13.2
ASOND	1459.3	4.2	8.1	12.2

*Record ends with August 2000 due to change of equipment and incompatible records.

Data provided by K. Orvis, from unpublished records of the Instituto Costarricense de Electricidad (ICE) for the "Repetidora Cerro de la Muerte" (station 073080). Mean precipitation is for 1971-2001, and temperature data are for the years 1971-2000. ICE has reported various elevations for the station. K. Orvis recently determined by differential GPS that the station elevation is 3466 m ± 0.6 m. The station location is 9° 33' 41"N, 83° 45' 18" W (K. Orvis, pers. comm.).

The sediments that I analyzed for this study were recovered from Lake 1 (3477 m; Fig. 2.2), previously referred to as Lago Morrenas, the largest lake in the upper part of the cirque at the base of Cerro Chirripó (Horn, in press). The lake has a surface area of 5.2 ha and its watershed is 90 ha. The lake is 225 m in diameter and mostly shallow (3–4 m) and flat bottomed, with the exception of an area 8.3 m deep near the eastern shore. This shore is adjacent to the wall of the valley, where the local relief is about 340 m; a 20 m high ridge surrounds the rest of the lake. Hastenrath (1973) interpreted it as moraine, but Orvis and Horn (2000) found that much of it is bedrock. An intermittent outlet connects Lake 1 to Lake 2 to the west.

2.4 Vegetation

The Chirripó páramo is the largest area of páramo in Costa Rica and it is located within one of the few areas of high montane environments in Central America. It straddles the crest of the Cordillera de Talamanca at its highest point, Cerro Chirripó (3819 m). Costa Rican páramos are small outliers of páramo vegetation, located north and west of the most extensive páramo regions in Colombia, Ecuador, Venezuela, and Peru. The páramos in Costa Rica do not reach elevations as high as the Andean páramos, and they lack a long history of settlement.

Grasses and shrubs dominate páramo vegetation (Luteyn, 1991). The grasses include a diverse array of bunch grasses. Dwarf bamboos, mainly *Chusquea subtesselata*, are common in the relatively moist Costa Rican páramos. The Costa Rican páramos are less diverse than the Andean páramos, perhaps in part because they occur in small patches, isolated from the larger areas of páramo vegetation in South America. The Costa Rican páramos are also unique because species of plants thought to have originated in North America are found there (Cleef and Chaverri, 1991). Table 2.2 lists common species in the Costa Rican páramos.

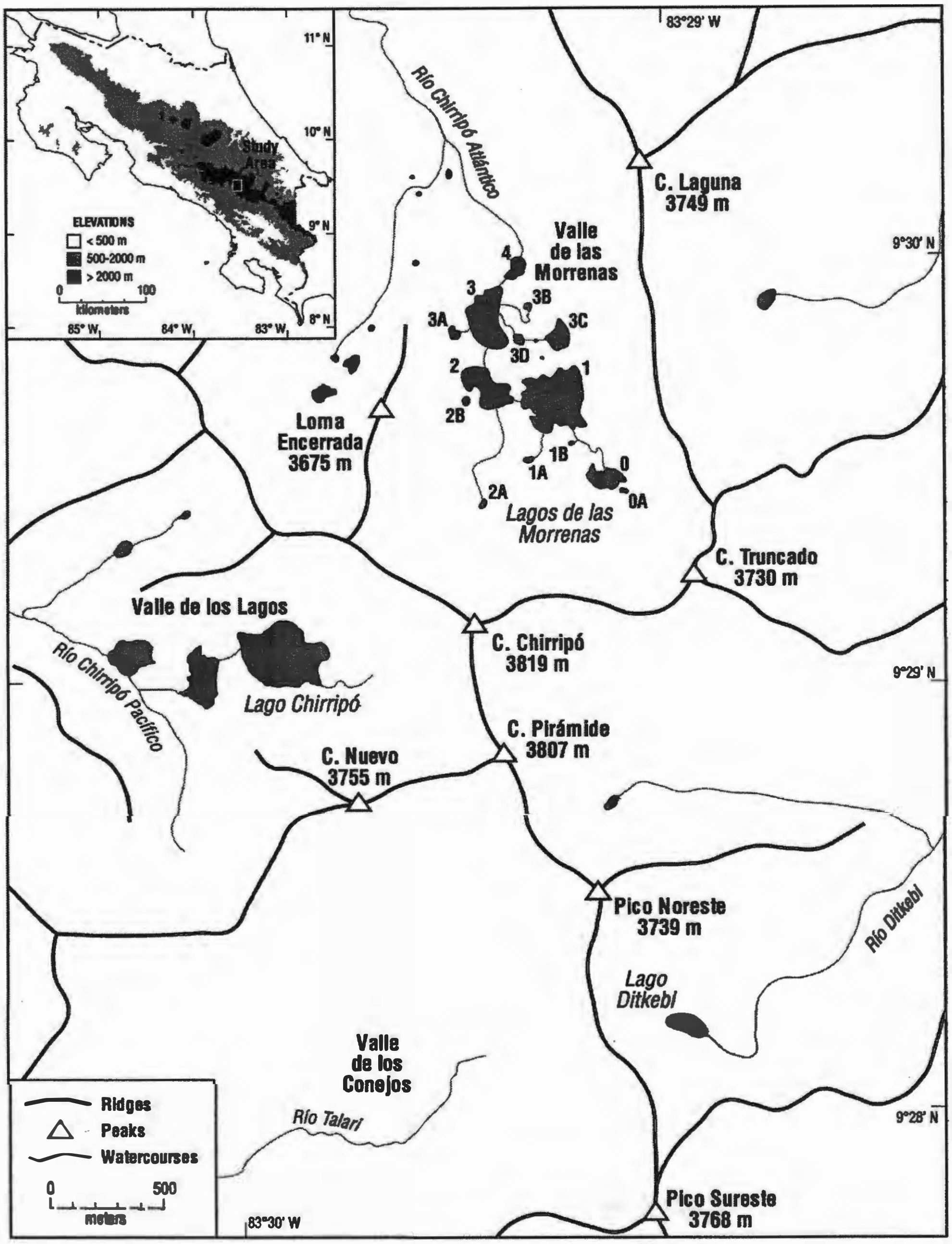

Figure 2.2 Map of the Chirripó Páramo Showing Valle de las Morrenas and Lake 1.
Source: from Orvis and Horn (2000) with slight modifications.

Table 2.2 Páramo Vegetation. Common plant taxa in the Costa Rican páramos.

Taxon	Physiognomic Description and Notes
Chusquea subtesselata	dwarf bamboo, most dominant species
Hypericum irazuense	small-leaved, evergreen shrub >50 cm
Vaccinium consanguineum	small-leaved, evergreen shrub >50 cm
Escallonia myrtilloides var. patens	small-leaved, evergreen shrub >50 cm
Hesperomeles heterophylla	small-leaved, evergreen shrub >50 cm
Myrsine dependens	small-leaved, evergreen shrub >50 cm
Pentacalia firmipes	small-leaved, evergreen shrub >50 cm
Senecio andicola	small-leaved, evergreen shrub >50 cm
Diplostephium costaricense	small-leaved, evergreen shrub >50 cm
Pernettya prostrata	small leaved, evergreen shrub <10 cm – >1 m*
Hypericum strictum	small leaved, evergreen shrub mainly <50 cm
Castilleja	semi-shrub mainly <50 cm
Cortaderia	tussock grass
Calamagrostis	tussock grass
Muhlenbergia flabellata	clump-forming grass
Agrostis	grasses
Carex	sedges
Bomarea acutifolia	herbaceous monocot, vine
Puya dasylirioides	terrestial bromeliad, up to 2 m
Valeriana prionophylla	herbaceous dicot
Acanea cylindrostachya	herbaceous dicot
Senecio oerstedianus	herbaceous dicot
Phytolacca rugosa	herbaceous dicot
Eryngium scaposum	herbaceous dicot
Gnaphalium	herbaceous dicot

(Continued)

Taxon	**Physlognomlc Description and Notes**
Alchemilla	herbaceous dicot
Azorella lehmanii	herbaceous dicot, cushion-forming
Blechnum buchtienii	arborescent
Elaphoglossum	fern
Jamesonia	fern, a primarily Andean genus
Lycopodium	club moss
Sphagnum	moss, cushion-forming
Isoetes	quillwort

* What Horn (1986, 1989) recognized as *Pernettya coriacea* is now known to be *P. prostrata.*
Source: Horn (1986, 1989, and in press).

Shrubs occur intermixed with the dominant bamboo, and make dense thickets along the lower edge of the páramo, and on rocky talus slopes. Some researchers have suggested that *Polylepis* shrubs grow on similar rocky sites in the Andes because the sites are fire protected, and others have suggested that these rocky sites create a microclimate more suitable for shrubs than for bamboo and herbs (Fjeldså, 1991). I have observed extensive fire scarring and resprouting of shrubs killed by fire in shrub thickets in the Valle de las Morrenas.

2.5 Fire and Páramo Vegetation

The Chirripó páramo does not have a history of permanent settlement, but fires have occurred at intervals for the past 10,000 years (Horn and Sanford, 1992; Hom, 1993; League, 1998; League and Horn, 2000). These fires could have been caused by lightning or by the occasional visitor from the lowlands. Fires could also have spread upslope from burning in the lowlands (Horn, 1993).

Horn (1989, 1990a) documented the recent history of fires in the Chirripó páramo from historical source material and interviews, and examined the impact of burning on páramo vegetation by measuring percent cover and postfire regrowth rates at four burn sites. Fires occurred in the Chirripó páramo in 1953, 1961, 1970, 1976, 1977, 1982, and 1985 (Horn, 1990a). Of these, the 1953, 1961, and 1976 fires reached the Valle Morrenas (Horn, 1990a and pers. comm.). The most recent páramo fire occurred in 1992, but burned mainly the oak forest below the páramos on the Pacific slope. It did not reach the Valle Morrenas (S. Horn, pers. comm.).

Horn (1989) studied postfire regeneration at three páramo burn sites in the Buenavista páramo and one in the Chirripó páramo. The time since the most recent fire at the sites ranged from 1 to over 12 years. Plants were classified as "dead," "resprouter," "postfire colonist," and "fire survivor." The change in species composition over time following burning was determined by comparing results for live and dead shrubs. The prefire and postfire heights of shrubs were measured to determine regrowth rates.

The research showed that *Chusquea subtessellata*, *Vaccinium consaguineum*, and many other common shrubs resprout following burning, but that herbs and shrubs are slow to colonize openings in the vegetation. The páramo vegetation is slow growing compared to vegetation in the lowland forests, and bare patches of ground can remain for ten or more years after a fire. The bamboo is the most vigorous resprouter and burning can increase its dominance. Successive fires at close intervals can reduce the population of certain species such as *Hypericum irazuense* that recolonize by seeding rather than sprouting (Horn, 1989).

2.6 Environmental History of the Chirripó Páramo

Information about the long-term environmental history of the Chirripó páramo comes from a series of studies based on analysis of sediment cores retrieved from the lakes that surround Cerro Chirripó. Horn (1993) recovered two sediment cores from Morrenas Lake 1 in January 1989. These cores are referred to as Core 1 and Core 2. Core 2 has been used for several analyses, including pollen and microscopic charcoal (Horn, 1993), macroscopic charcoal (League and Hom, 2000), diatoms (Haberyan and Horn, 1999), and stable carbon isotopes (Lane *et al.*, 2002; Lane, 2003).

Core 1 and Core 2 were retrieved with a square-rod piston corer (Wright *et al.*, 1984). Horn used PVC pipe fitted with a rubber piston to collect the uppermost sediments. Core 2 was 5.6 m long, and was recovered from a water depth of 7.5 m. Core 1 was 6 m long, and was recovered from a depth of 5.4 m. Table 2.3 shows the ^{14}C dates from Core 2, and Figure 2.3 shows the location of these coring sites.

Hom's (1993) study was done to reconstruct the postglacial vegetation and fire history of the Chirripó páramo. The results of this investigation indicated that the high peaks have supported páramo vegetation similar to that of the present throughout the Holocene, and that fires have occurred regularly for the past 10,000 radiocarbon years, with an increase in microscopic charcoal during the last half of the Holocene.

Horn (1989, 1993) also examined the microscopic charcoal in a 4000-year core from nearby Lago Chirripó (Fig. 2.2). Microscopic charcoal peaks showed a good match with those in the Morrenas Lake 1 record. The Lago Chirripó sediment core also contained two distinct lenses of macroscopic charcoal. Horn hypothesized that these layers may have been deposited during a period of drier climate and lower lake level (Horn and Sanford, 1992).

League and Hom (2000) analyzed macroscopic charcoal in Core 2 by wet-sieving contiguous samples through nested screens of 125, 250 and 500 µm. Charcoal fragments greater than 500 µm were counted with a dissecting microscope, and the presence or absence of fragments in the 125-250 µm and 250-500 µm size classes was noted. The charcoal fragments in the size classes less than 500 µm were not counted because they were obscured by macroinvertabrate fecal colloids. The macroscopic charcoal analysis revealed that fires burned in the Chirripó páramo at intervals throughout the Holocene.

It is possible that regional fires that did not burn the páramo produced the microscopic charcoal in Lake 1, but the macroscopic charcoal in the Lake 1 sediments confirmed that the charcoal was likely due to local burning (League, 1998; League and Horn, 2000). The

Table 2.3 Core 2 Radiocarbon Dates for Morrenas Lake 1 Core 2.

Laboratory Number	Sediment Interval	Uncalibrated ^{14}C age (^{14}C yr BP)	Calibrated age range (cal. yr BP ± 2σ)
β-30431	81–111 cm	1230 ± 170	1510–790
β-30432	215–236 cm	3100 ± 90	3470–3080
β-30433	315–335 cm	4250 ± 90	5040–4530
β-30434	415–435 cm	6830 ± 120	7930–7440
β-30435	515–527 cm	8900 ± 100	10,240–9600
β-30787	527–542.5 cm	10,140 ± 120	12,360–11,230

Radiocarbon determinations were made by Beta Analytic Laboratory. Calibrations were determined using version 4.3 of the CALIB radiocarbon age calibration program (Stuiver and Reimer, 1993) and are based on data sets of Stuiver *et al.* (1998). Source: from Horn and League (in press).

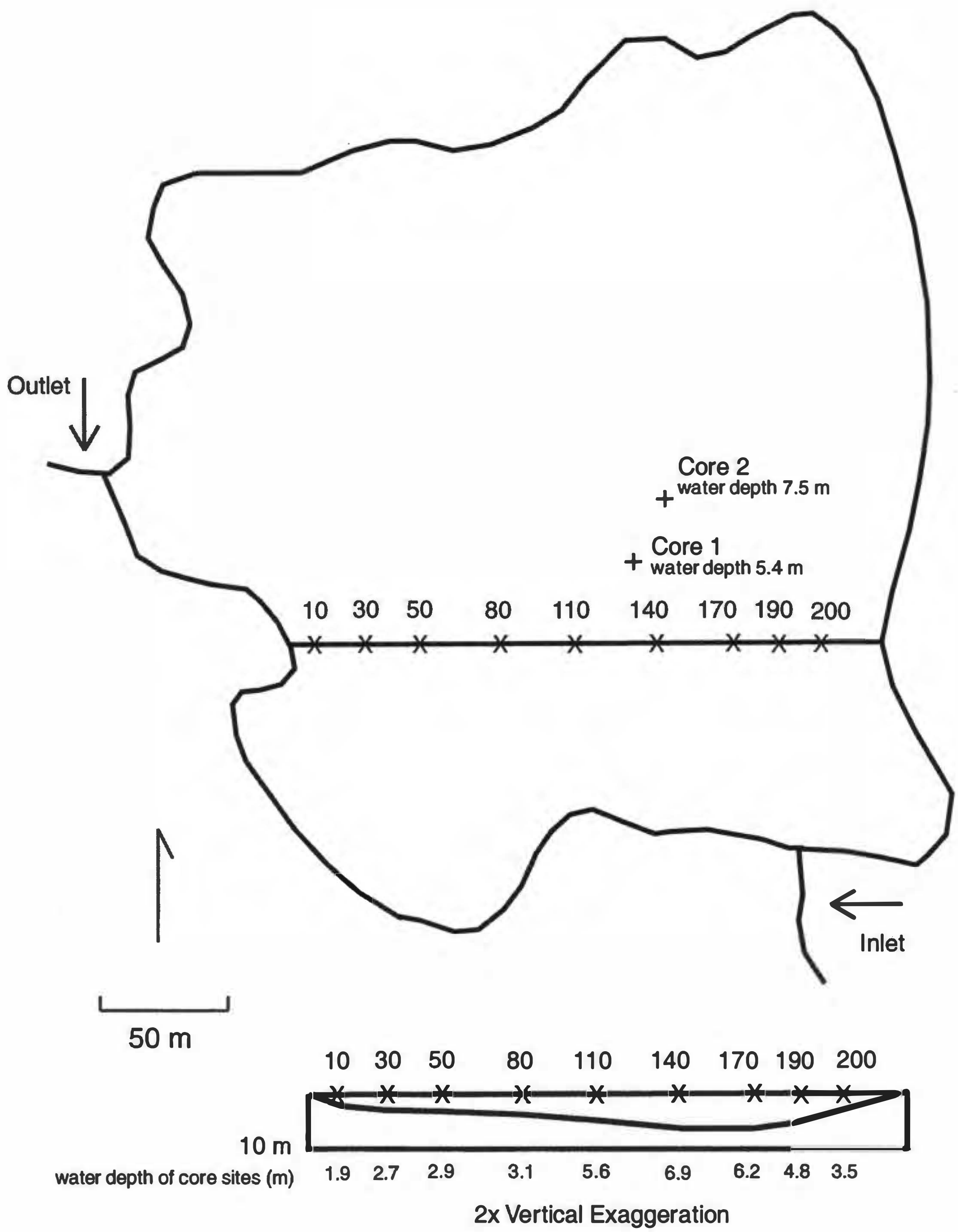

Figure 2.3 Sediment Core Sites in Lake 1. The short (<30 cm) sediment cores for this study were recovered in February 1998 along the transect, and are named based on their distance in meters from the western shore. Long (>5 m) sediment cores from sites 1 and 2 were recovered in 1989. The lake outline is based on a map in Horn (1993).

macroscopic charcoal analysis revealed several fire events missed by the microscopic charcoal analysis, and also showed more clearly a period of fewer fires in the early Holocene.

The interpretation of the macroscopic charcoal record from Lake 1 as confirming local, or watershed fires, is weakened by evidence from Oregon lakes that revealed that low levels of macroscopic charcoal can be transported to lakes in unburned watersheds (Gardner and Whitlock, 2001), presumably by wind during a fire. The largest charcoal peaks in the long-term record from Lake 1 consisted of no more than 35 individual charcoal fragments. A strong confirmation of local fires may require larger numbers of fragments, and finding large numbers of fragments may require analyzing smaller size classes of charcoal (*e.g.*, 125–500 µm). Evidence showing that the patterns of charcoal concentration are similar in different size classes would strengthen the long term sedimentary charcoal record from Lake 1 that is based on a size class (>500 µm) with low numbers of charcoal fragments.

In their investigation of the diatoms of Lake 1, Haberyan and Horn (1999) discovered that the species composition of the diatom community has remained stable throughout the Holocene. In Lake 1, peaks in diatom abundance correspond with microscopic charcoal peaks. The microscopic charcoal peaks in Lake 1 also correspond to one of the macroscopic charcoal layers observed in sediments from nearby Lago Chirripó (Hom, 1993). This peak at 2430 ^{14}C yr BP corresponds to a period of drier climate in the circum-Caribbean suggested by Hodell *et al.* (1995). A peak in microscopic charcoal in Morrenas Lake 1 Core 2 (Horn, 1993) also corresponds to a dry period proposed by Curtis *et al.* (1996) at ~1200 ^{14}C yr BP, and to the other lens of macroscopic charcoal in the Lago Chirripó sediment core.

Horn (1990b) and Orvis and Horn (2000) studied the timing of deglaciation in the Valle de las Morrenas based on radiocarbon dates on charcoal and bulk organic sediments in cores from glacial lakes. Based on cores from Lakes 0A, 1, and 4, Orvis and Horn (2000) concluded that the most recent deglaciation occurred some time after 12,300 cal. yr BP and before 9700 cal. yr BP. They concluded that the last glacial advance preceeding deglaciation corresponded in global terms to the Younger Dryas event (12,900–11,600 cal. yr BP). Orvis and Horn (2000) also described evidence of previous glaciations that were more extensive than previously thought.

Lane *et al.* (2002), and Lane (2003) investigated the stable carbon isotope stratigraphy of Core 1 and Core 2 from Morrenas Lake 1 to explore late Pleistocene and Holocene C_3 and C_4 vegetation dynamics. They found shifts in carbon isotope values suggesting that C_4 grasses may have been a more important component of the páramo vegetation during the late Pleistocene and earliest Holocene. They also found that sediment intervals in Core 2 with high macroscopic charcoal concentrations, and intervals in Core 1 corresponding to charcoal-rich sections of Core 2, had more depleted carbon isotope compositions. The total organic carbon in the stratigraphic record of Morrenas Lake 1 is not related to fires, but it appears that the carbon budget of Lake 1 is influenced by charcoal influx that leads to a larger allocthonous component of the total organic carbon (Lane, 2003).

3.0 Methods

3.1 Introduction

My study is a detailed examination of the pattern of charcoal concentration in the uppermost sediments of a páramo lake. I retrieved nine short sediment cores that preserved the sediment-water interface along a transect that crossed the lake. I took samples from the top 20 cm of these cores at contiguous 1-cm intervals, and wet-sieved them through four nested sieves to generate 540 potential subsamples for counting macroscopic charcoal. I used the results of sieving to create a picture of where the charcoal is concentrated in the uppermost lake sediments, and I analyzed this information to draw inferences about the physical processes that caused the pattern of charcoal concentration. In this chapter I describe the field methods used to collect sediment samples, the techniques that were used to attempt to establish the age of the sediment, and the methods used to quantify the charcoal content of the samples.

3.2 Field Sampling

With Sally Horn and Ken Orvis, I collected a series of short sediment cores from Lago Morrenas 1 in February 1998. I stretched a rope across the lake and marked it off in 10 m increments (Fig. 2.3). I collected a total of nine cores along the transect at 10, 30, 50, 80, 110, 140, 170, 190, and 200 m from the western shore. I refer to these cores by their position along the transect, e.g., Core 30, Core 110.

I collected the short cores (each 20–30 cm long) along the transect across the lake using a gravity corer designed by Steve Klein. This gravity, or Klein, corer is the same as the corer used by Millspaugh and Whitlock (1995) in their study of recent charcoal stratigraphy in Yellowstone National Park. This device preserves the stratigraphy of the sediments at the sediment-water interface. While in the field, I extruded the cores in 1 cm intervals and placed the resulting samples in plastic bags for storage. The portion of each core that extended deeper than 20 cm was extruded by 3 cm intervals and stored. The samples taken from a depth more than 20 cm below the sediment-water interface were not analyzed in this study.

3.3 Chronology

^{210}Pb is a low-energy radionuclide that occurs naturally in the environment. It is a granddaughter decay product of ^{226}Ra, which is common in soils. The decay of ^{226}Ra in soils results in the outgassing of Radon. The decay of Radon gas in the atmosphere results in ^{210}Pb, which precipitates out of the atmosphere with rainfall and is deposited, sometimes in lake sediments. The half-life of ^{210}Pb is 22.3 years, making it ideal for dating sediments that are less than 500 years old (Nittrouer *et al.*, 1984).

I.L. Larsen, of the Environmental Sciences Division of the Oak Ridge National Laboratory, quantified the ^{210}Pb in the Core 50 short core by gamma-ray spectrometry with the technique described by Cutshall *et al.* (1983). Larsen also tested sediments from Lake 1 for ^{137}Cs. ^{137}Cs is now found in the natural environment due to bomb testing in the 1950s. ^{137}Cs can also help date sediments that are less than 100 years old (Nittrouer *et al.*, 1984).

3.4 Charcoal Quantification

Following Millspaugh and Whitlock (1995), I sieved the sediment from the short cores through nested sieves with mesh sizes of 1000, 500, 250, 125, and 63 µm, and counted the charcoal particles on the 500, 250, and 125 µm screens with a binocular stereomicroscope. I treated each sample in hot KOH for one hour prior to sieving to reduce the amount of non-charcoal organic material clogging the screens. The charcoal fragments on the 63 µm screen were too small and numerous to count, but they were washed into petri dishes, dried, and stored for possible future study.

3.5 KOH Experiment

The sediment from Lake 1 is composed almost entirely of organic colloids that appear to be zooplankton fecal pellets. Using deionozed water and no pretreatment, many of these colloids would not pass through the 125 and 250 µm sieves. They obscured the charcoal on those screens, making it impossible to count the charcoal fragments. I needed to find a way to remove these colloids without affecting the charcoal in the sediments.

Other researchers experiencing this have treated the sediment with a weak solution of sodium hypochlorite (C. Whitlock, pers. comm. to Sally Horn). Because that method may possibly bleach the charcoal particles (Clark, 1983) or may not be as effective with the Lake 1 sediments, I experimented with several chemical treatments, including sodium hypochlorite in the form of commercial laundry bleach, sodium hexametaphosphate, and potassium hydroxide (KOH). The bleach treatment broke down the organic material and allowed it to pass through the seives. The sodium hexametaphosphate, which changes the charges of particles in solution so that they disperse, did not make it any easier to sieve the the material through 125 and 250 µm sieves, although the material did pass more easily through the 500 µm sieve.

The chemical treatment with KOH made the sediment sieve as effectively as the treatment with bleach. Because of concerns about the bleaching of the charcoal, I decided to use the KOH treatment. I conducted an experiment with the KOH treatment to explore the extent to which the charcoal might be damaged by KOH.

I crushed modem charcoal that was collected from a campfire, and then separated it into twelve samples of ~1 g each by coning and splitting. I sieved each sample, separating them into subsamples of 125–250 µm, 250–500 µm, and 500–1000 µm size fractions. I determined the weight of each subsample, and then mixed them back together into the twelve original samples. Nine of those were treated with 10% KOH in a hot water bath, and three were left untreated as controls. Of the nine treated with KOH, three were treated in the hot water bath for ten minutes, three for 30 minutes, and three for 60 minutes. After the chemical treatments, I re-sieved the samples, and determined the weights of each size fraction. Table 3.1 shows the results of this experiment.

The purpose of this experiment was to examine how pretreatment of sediment samples would affect charcoal, specifically whether or not pretreatment would destroy charcoal. I did not intend to control for every possibility in this experiment, and I did not intend to analyze the results

Table 3.1 Charcoal Loss from KOH Pretreatment. Each charcoal sample weighed ~1 g. Values show the percent decrease in mass for each sample so that negative numbers indicate an increase in mass. The value for the 30 min. KOH 2 in the 500–1000 μm size class shows that the weight increased by an amount that cannot be reasonably explained by anything other than a notation error at the time of laboratory analysis.

Sample	**125–250 μm**	**250–500 μm**	**500–1000 μm**
Control 1	27.9	14.9	-7.8
Control 2	19.7	-3.0	1.4
Control 3	13.1	13.9	-0.7
10 min. KOH 1	6.9	-3.0	-6.3
10 min. KOH 2	27.4	-6.4	-13.8
10 min. KOH 3	4.4	-18.6	-13.7
30 min. KOH 1	-17.9	2.8	-8.4
30 min. KOH 2	13.4	-18.0	-337.4
30 min. KOH 3	12.2	-28.7	-11.2
60 min. KOH 1	-5.1	5.4	-15.4
60 min. KOH 2	17.8	-30.9	-15.6
60 min. KOH 3	-6.8	91.5	-11.6

with rigorous statistics. The results of this experiment suggest that any damage to the charcoal fragments by the KOH, such as breaking them into smaller particles or dissolving them, is negligible. The samples treated with KOH did not generally decrease in mass more than the control samples. Most of the samples treated with KOH actually increased in mass. This is probably due to adsorption of KOH by the charcoal (K. Orvis, pers. comm.). The fact that three control samples showed an increase in mass is probably because the charcoal was very dry after removal from the dessicator, and the charcoal absorbed moisture from the air between the time it was removed from the dessicator and the time it was weighed. Every possible effort was made to minimize this type of error, but the evidence nonetheless indicates that pretreatment with KOH does not destroy charcoal.

3.6 Core 200

The charcoal in Core 200 could not be quantified with the wet-sieving method used for the other cores. The charcoal particles from samples of this core were too numerous to distinguish visually on the screens. The samples on which I attempted counting had far more than 500 charcoal fragments. Just over 500 fragments in a sample is my upper limit for obtaining reliable counts. In order to have some quantitative data from this core, I washed the charcoal into pre-weighed petri dishes, and dried and re-weighed them to determine the dry mass of charcoal in the three size fractions.

3.7 Diagrams and Descriptive Statistics

Charcoal diagrams of several types were produced using a modified version of CalPalyn (Bauer *et al*., 1991) running on a Linux platform, and using Microsoft Excel. Sally Horn and I produced diagrams based on particle concentration (fragments/cc wet sediment). We also produced diagrams that show the percent abundance for each core and each size class. This expresses the charcoal abundance at each level of each core as a percent of the total amount of charcoal in all samples of the core. This scales the abundance figure for each size class and allows for an easy visual comparison of the abundance pattern between size classes.

Using Excel, I also calculated and graphed charcoal influx for Core 140. Influx is expressed as charcoal fragments/cm^2/year, which is equivalent to the charcoal concentration divided by the number of years represented within each 1 cm slice of the core. I used two models developed by Ken Orvis to estimate the number of years in each 1 cm slice of the core. Both models were based on the uppermost ^{14}C date in Core 2 from Morrenas Lake 1. I calculated influx for Core 140 because it was located closest to the site of Core 2 (Fig. 2.3) for which Horn (1993) obtained radiocarbon dates.

I also calculated the total accumulation of charcoal for each core. This is based on a concept that has been used to describe the accumulation of radioisotopes in lake sediments (I.L. Larsen, pers. comm.). It is expressed as the number of particles per square cm of surface area. I calculated this statistic by summing the charcoal fragment counts for each of the twenty levels in each core, and dividing that sum by the area of the core tube. This produced a diagram that allows for easy visual comparison of total charcoal accumulation in the upper 20 cm of sediment at each coring site along the transect.

4.0 Results

4.1 Introduction

In this chapter, I present the results of the ^{210}Pb and ^{137}Cs analyses and the charcoal quantifications. The charcoal quantifications fall into two broad categories. The first category is the comparison of charcoal fragment size classes within each core. The second is a comparison of charcoal abundance at each core site. I show the total accumulation of charcoal at each core site along the transect, and a calculation of charcoal influx for Core 140 based on two chronologies derived from a radiocarbon date on Morrenas-1 Core 2. I also present information about Core 200, which was not sieved due to the extremely high abundance of charcoal.

4.2 Radioisotope Analysis

In Core 50 (used for ^{210}Pb analyses), ^{210}Pb was detected only in the upper 4 cm (0–1 cm, 1–2 cm, 2–3 cm, and 3–4 cm samples, Table 4.1). The levels of ^{210}Pb do not decrease gradually with depth. The ^{210}Pb quantity fluctuates in the upper 4 cm, and in all of the samples below the 3–4 cm sample, the quantity of ^{210}Pb was below the minimum detectable limits. ^{137}Cs and ^{226}Ra were also below the minimum detectable limits in the samples that were analyzed for ^{210}Pb.

4.3 Size Class Comparison

Figures 4.1 through 4.8 show the percentage-based charcoal curves for each core, with all three size classes for each core on the same diagram.

4.4 Core Site Comparison

Figures 4.9 through 4.11 show the charcoal concentrations for each core. These diagrams allow comparison of the charcoal stratigraphy of each core along the transect. Each diagram shows the charcoal curve for one size class of charcoal at all of the core sites.

Table 4.1 Core 50 ^{210}Pb Quantity. ^{210}Pb is expressed in Picocuries per gram wet weight.

Sample depth	**^{210}Pb Pci/g**
0–1 cm	32.4 ± 2.9
1–2 cm	43.5 ± 8.8
2–3 cm	21.1 ± 3.0
3–4 cm	42.2 ± 6.1
4–5 cm	0
6–7 cm	0
10–11 cm	0

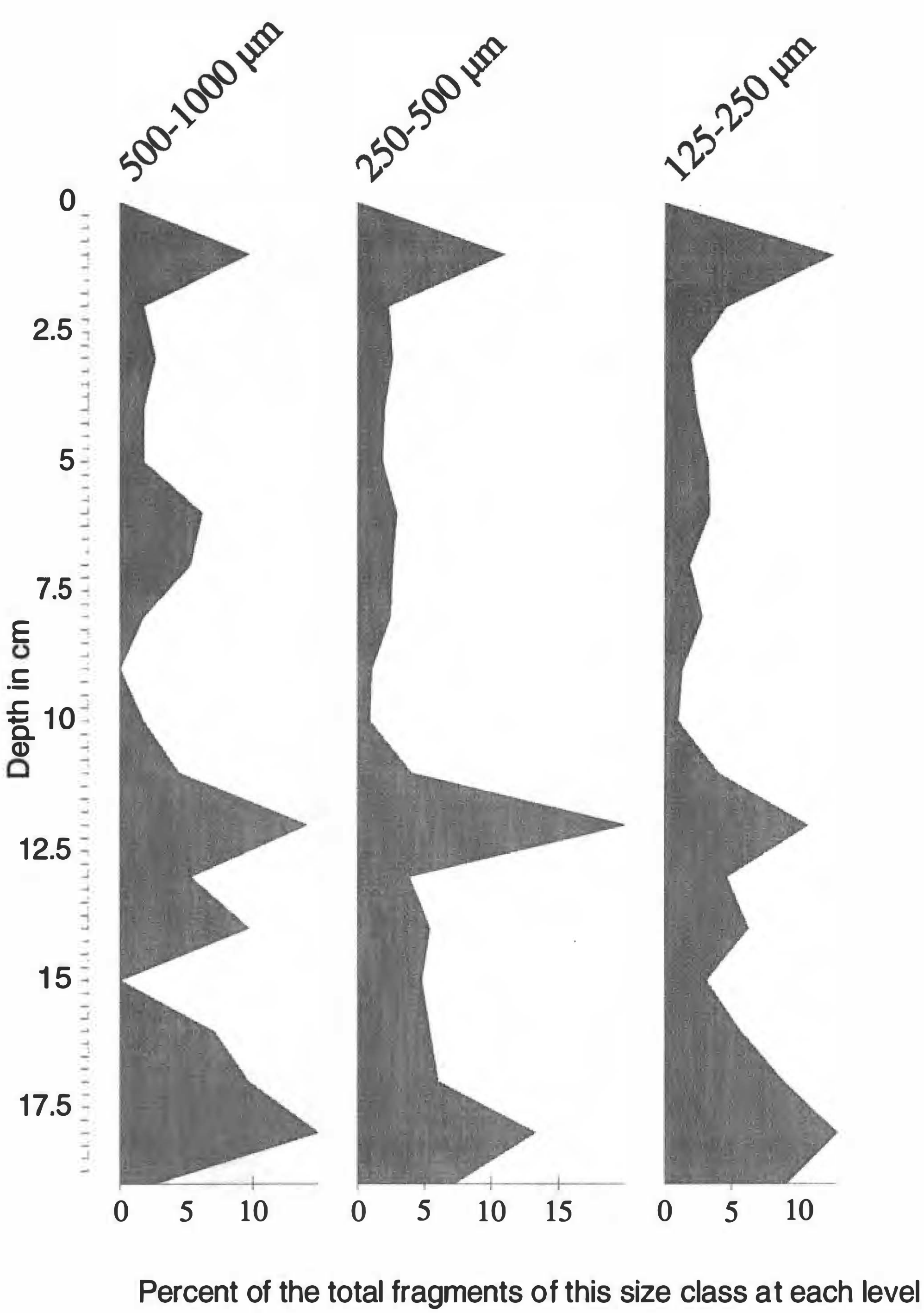

Figure 4.1 Core 10 Size Class Comparison. This figure shows the percent values for the 500–1000 µm, 250–500 µm, and 125–250 µm size classes for core 10. The curves for each size class show the percentage of charcoal in that size class at each depth. Each column sums to 100%. The uppermost sample for core 10 (0–1 cm) was accidentally destroyed.

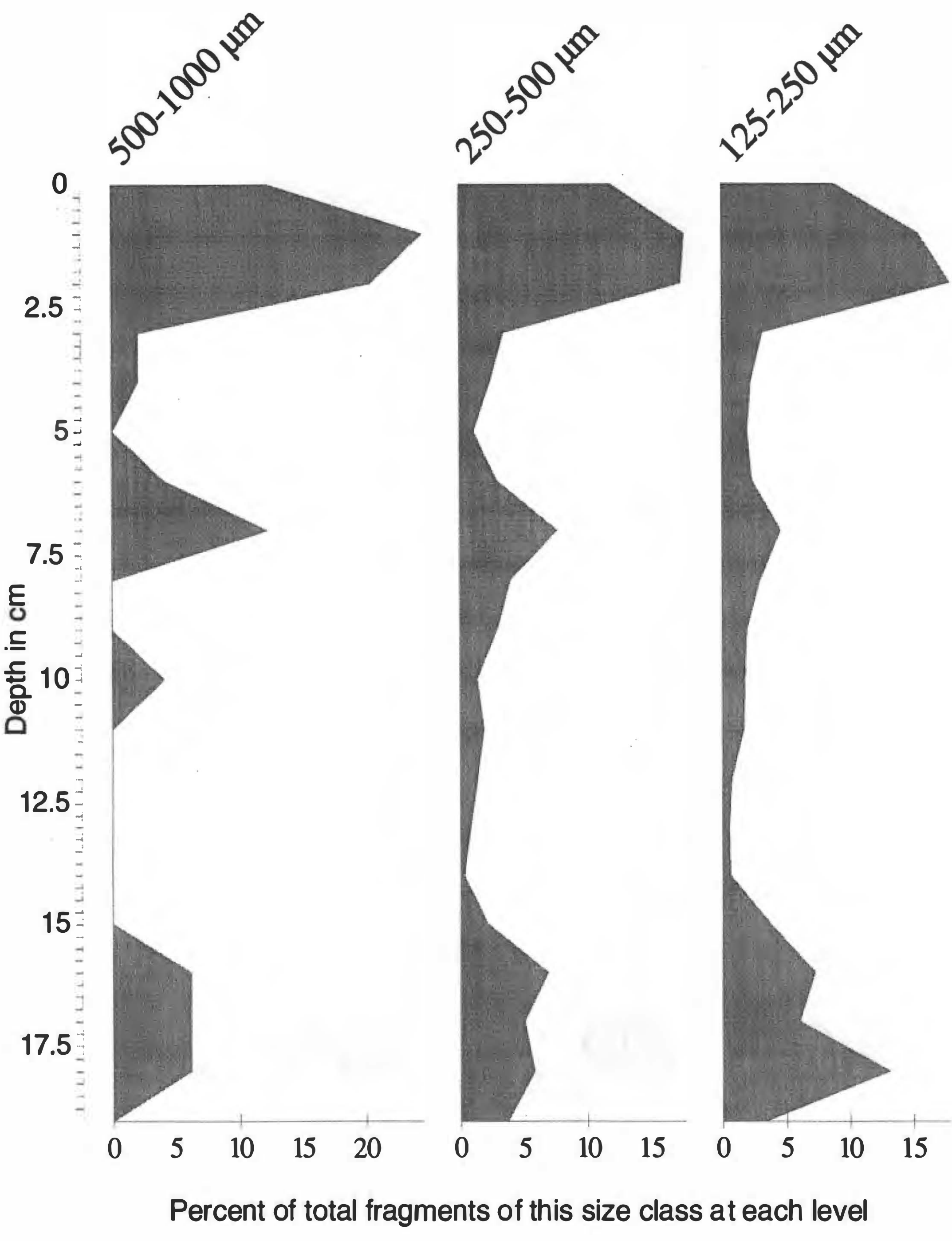

Figure 4.2 Core 30 Size Class Comparison. This figure shows the percent values for the 500–1000 µm, 250–500 µm, and 125–250 µm size classes for core 30. The curves for each size class show the percentage of charcoal in that size class at each depth, so each column sums to 100%.

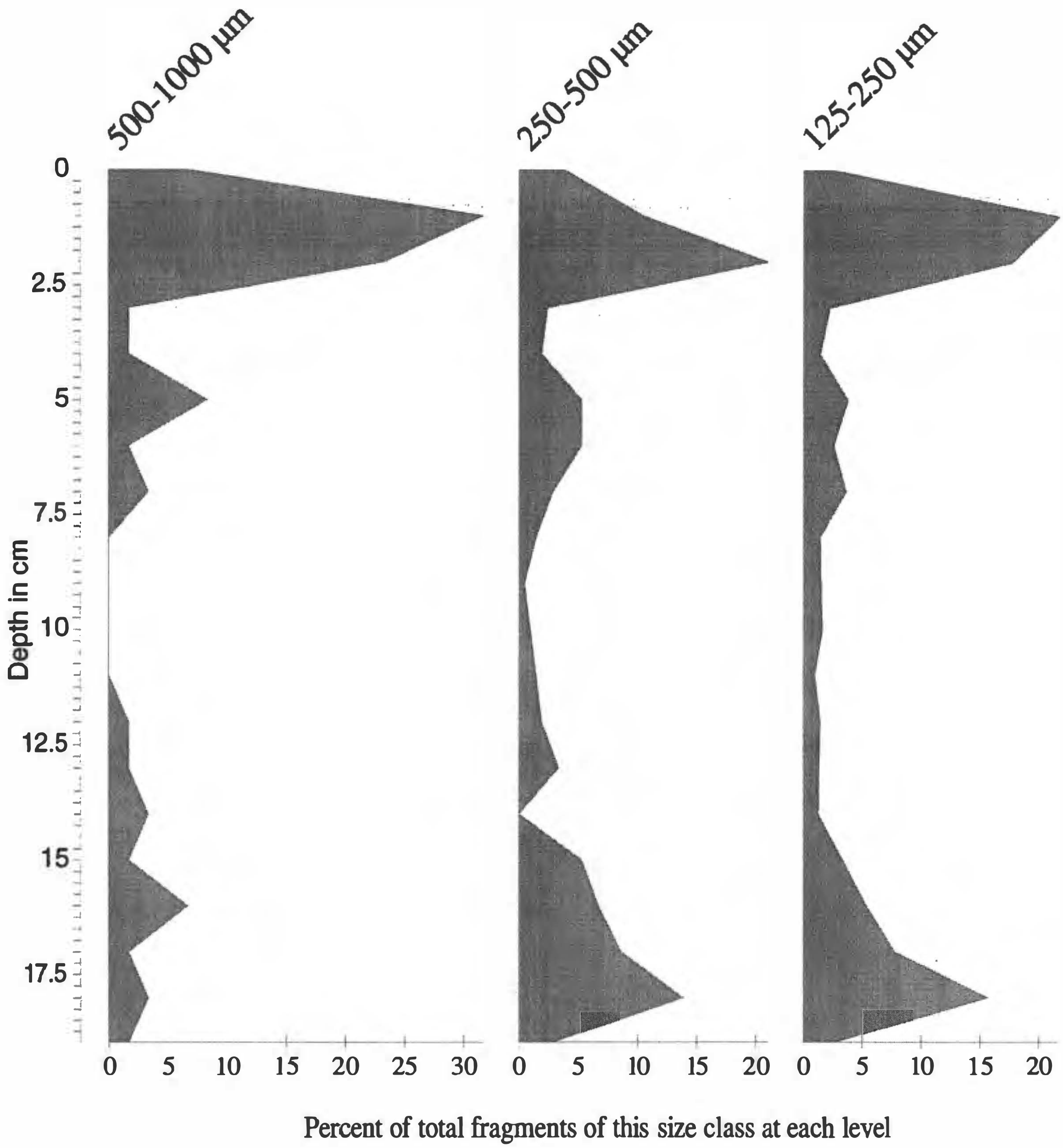

Figure 4.3 Core 50 Size Class Comparison. This figure shows the percent values for the 500–1000 µm, 250–500 µm, and 125–250 µm size classes for core 50. The curves for each size class show the percentage of charcoal in that size class at each depth, so each column sums to 100%.

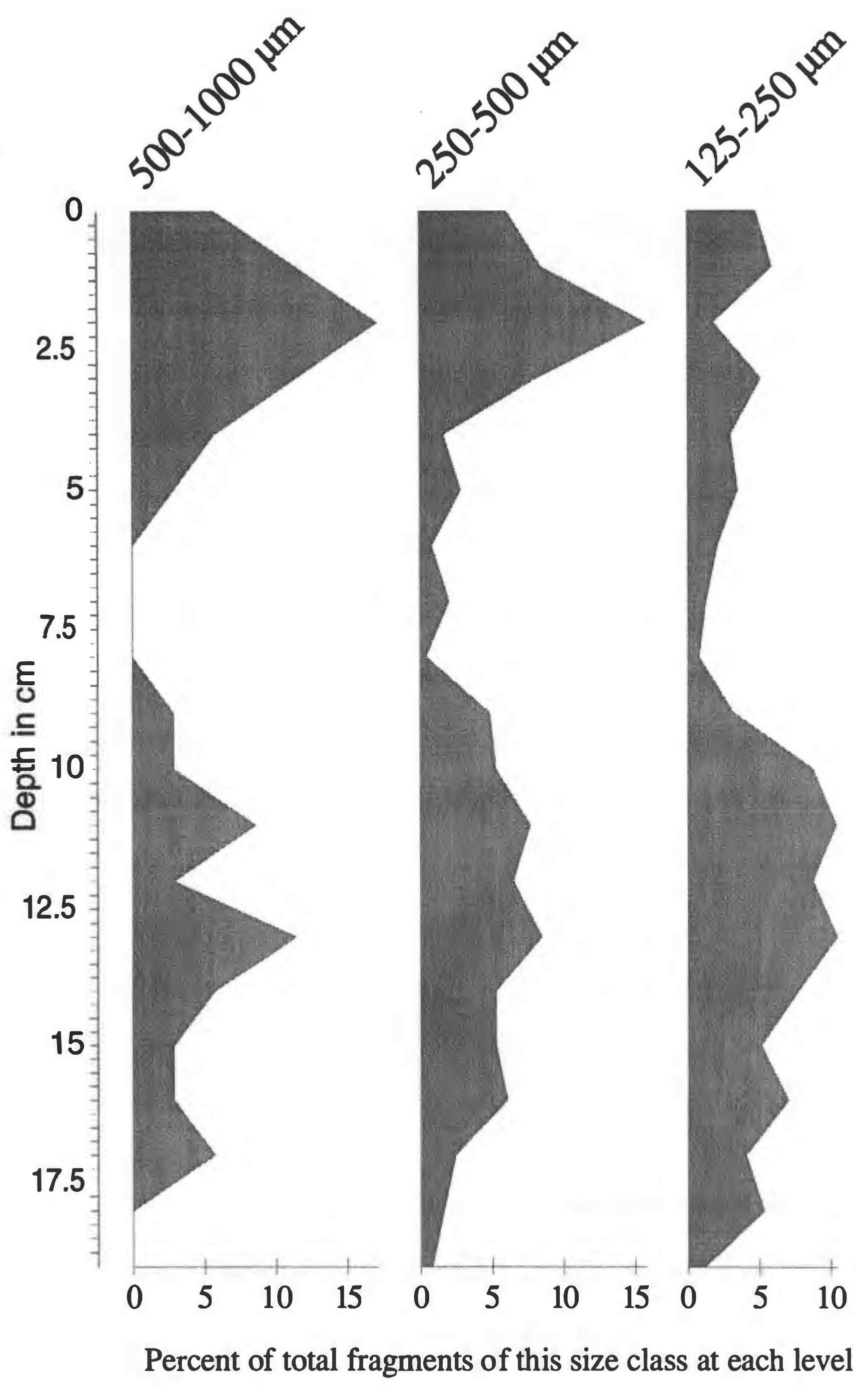

Figure 4.4 Core 80 Size Class Comparison. This figure shows the percent values for the 500–1000 µm, 250–500 µm, and 125–250 µm size classes for core 80. The curves for each size class show the percentage of charcoal in that size class at each depth, so each column sums to 100%.

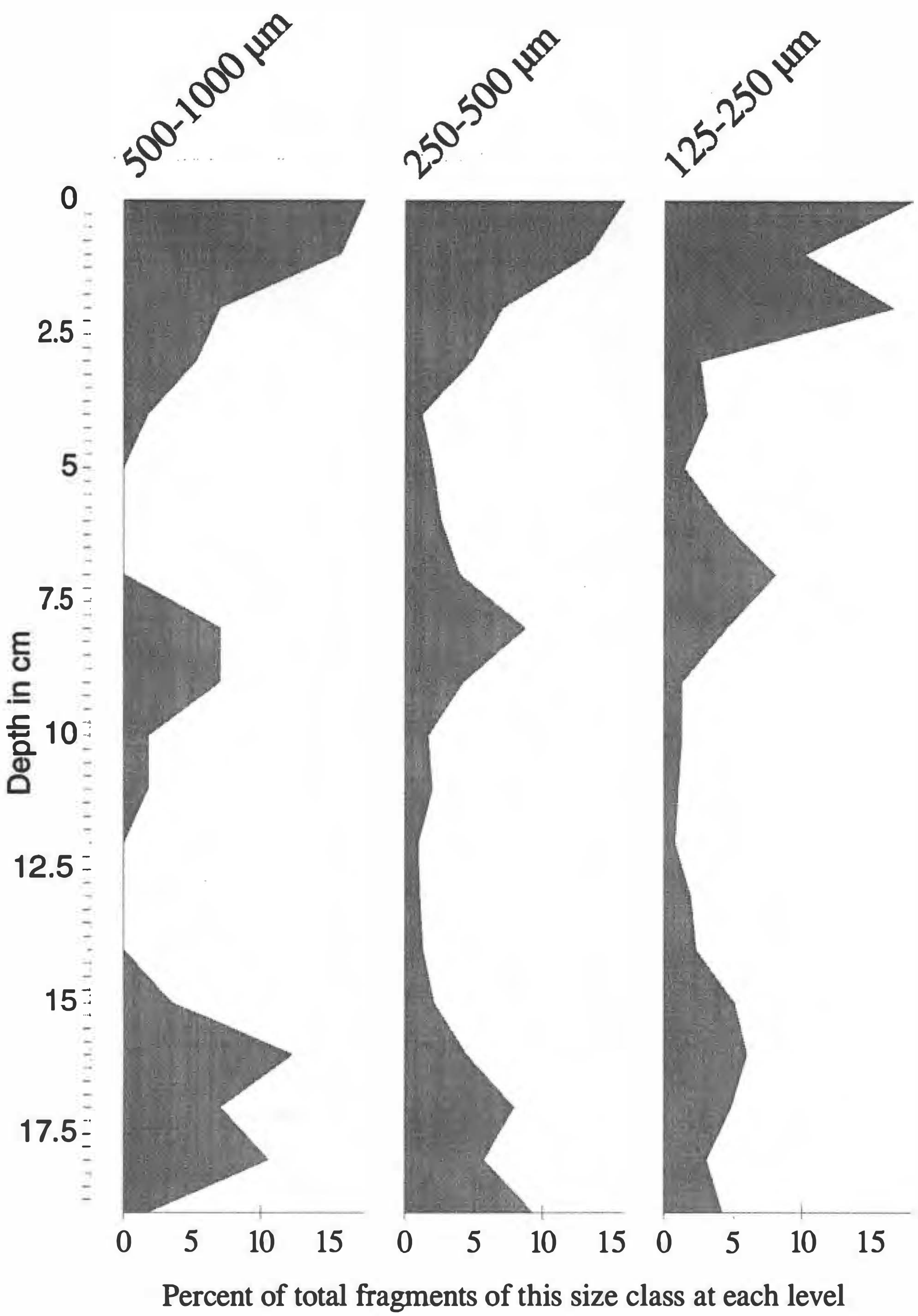

Figure 4.5 Core 110 Size Class Comparison. This figure shows the percent values for the 500–1000 μm, 250–500 μm, and 125–250 μm size classes for core 110. The curves for each size class show the percentage of charcoal in that size class at each depth, so each column sums to 100%.

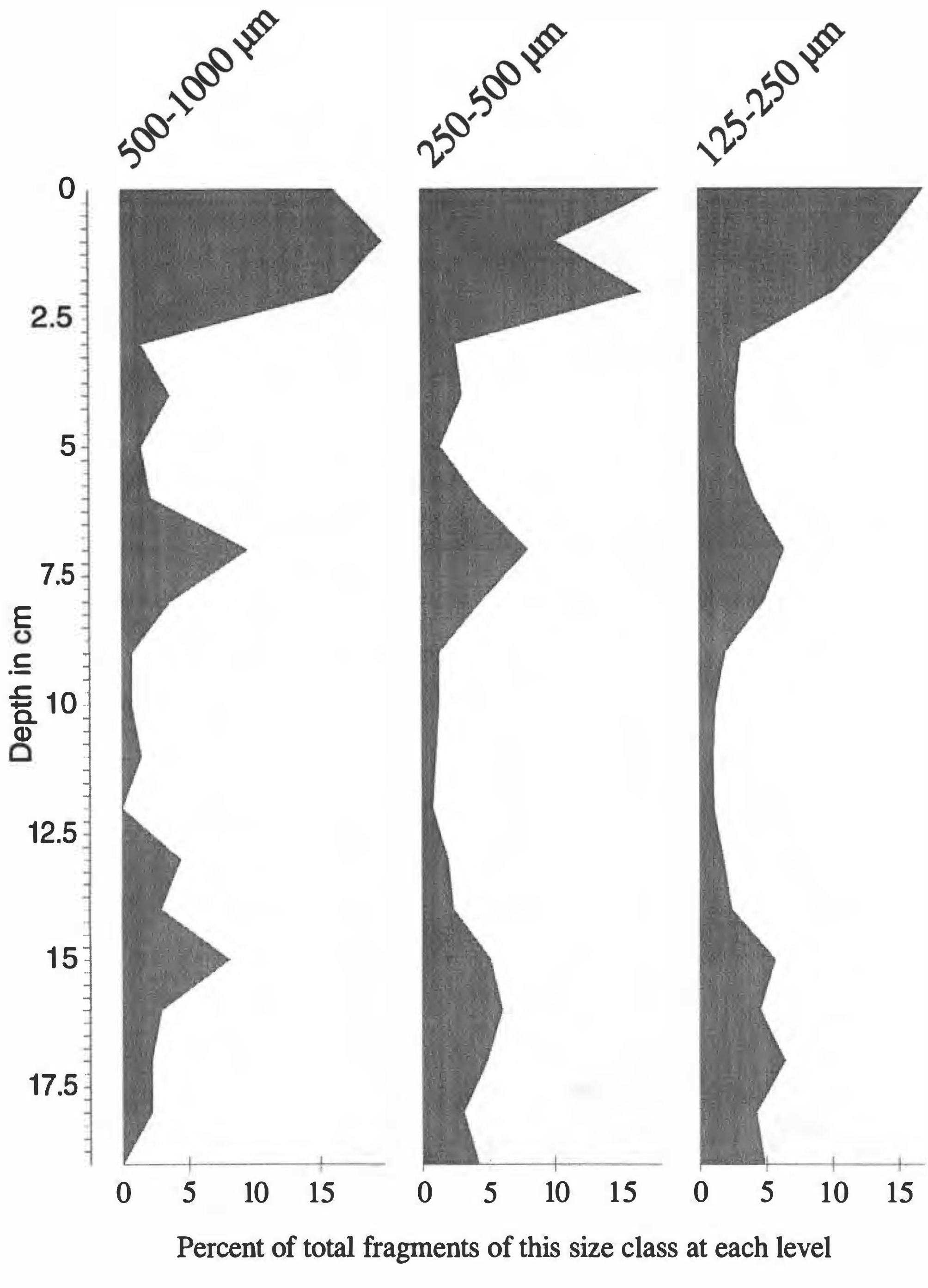

Figure 4.6 Core 140 Size Class Comparison. This figure shows the percent values for the 500–1000 µm, 250–500 µm, and 125–250 µm size classes for core 140. The curves for each size class show the percentage of charcoal in that size class at each depth, so each column sums to 100%.

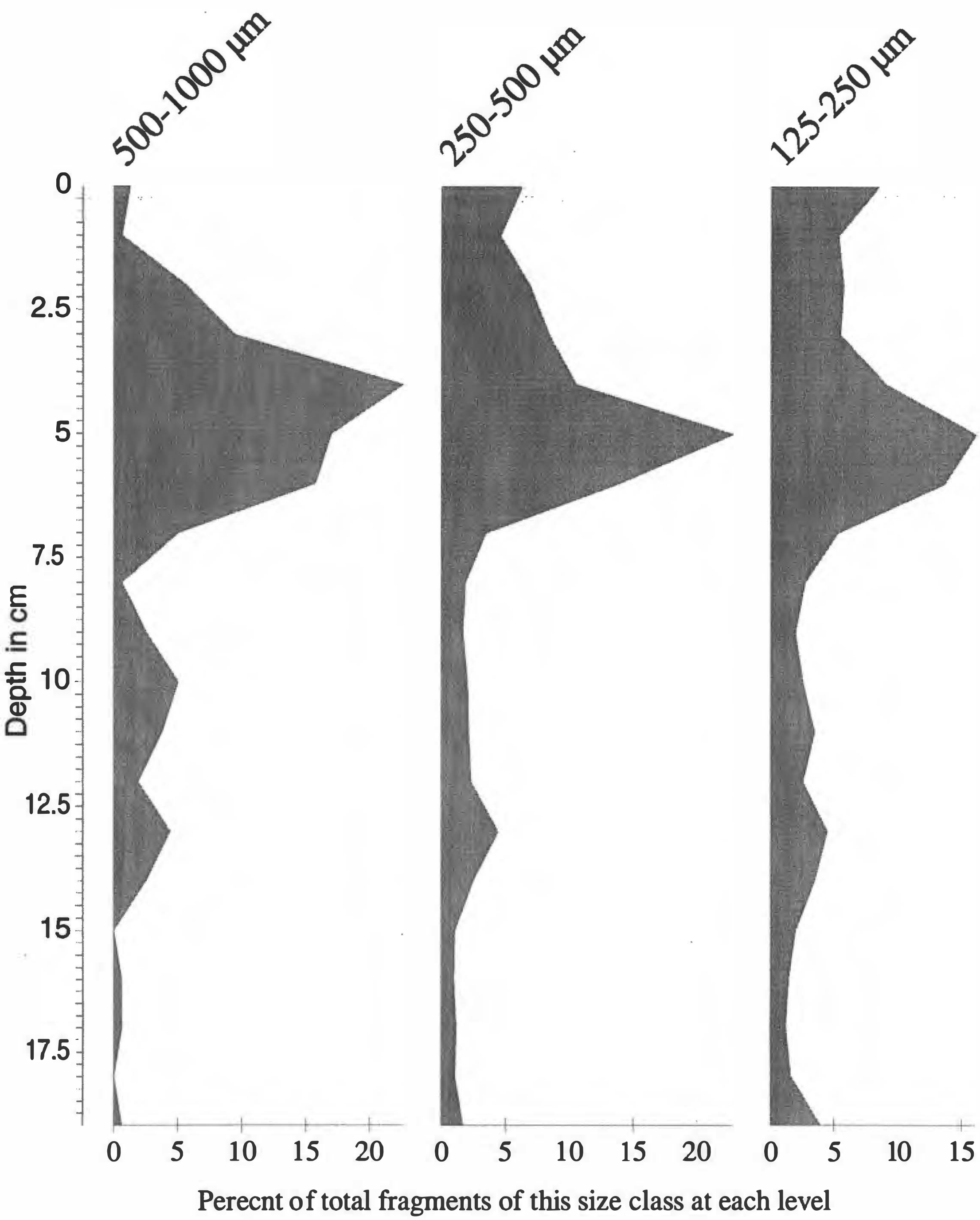

Figure 4.7 Core 170 Size Class Comparison. This figure shows the percent values for the 500–1000 µm, 250–500 µm, and 125–250 µm size classes for core 170. The curves for each size class show the percentage of charcoal in that size class at each depth, so each column sums to 100%.

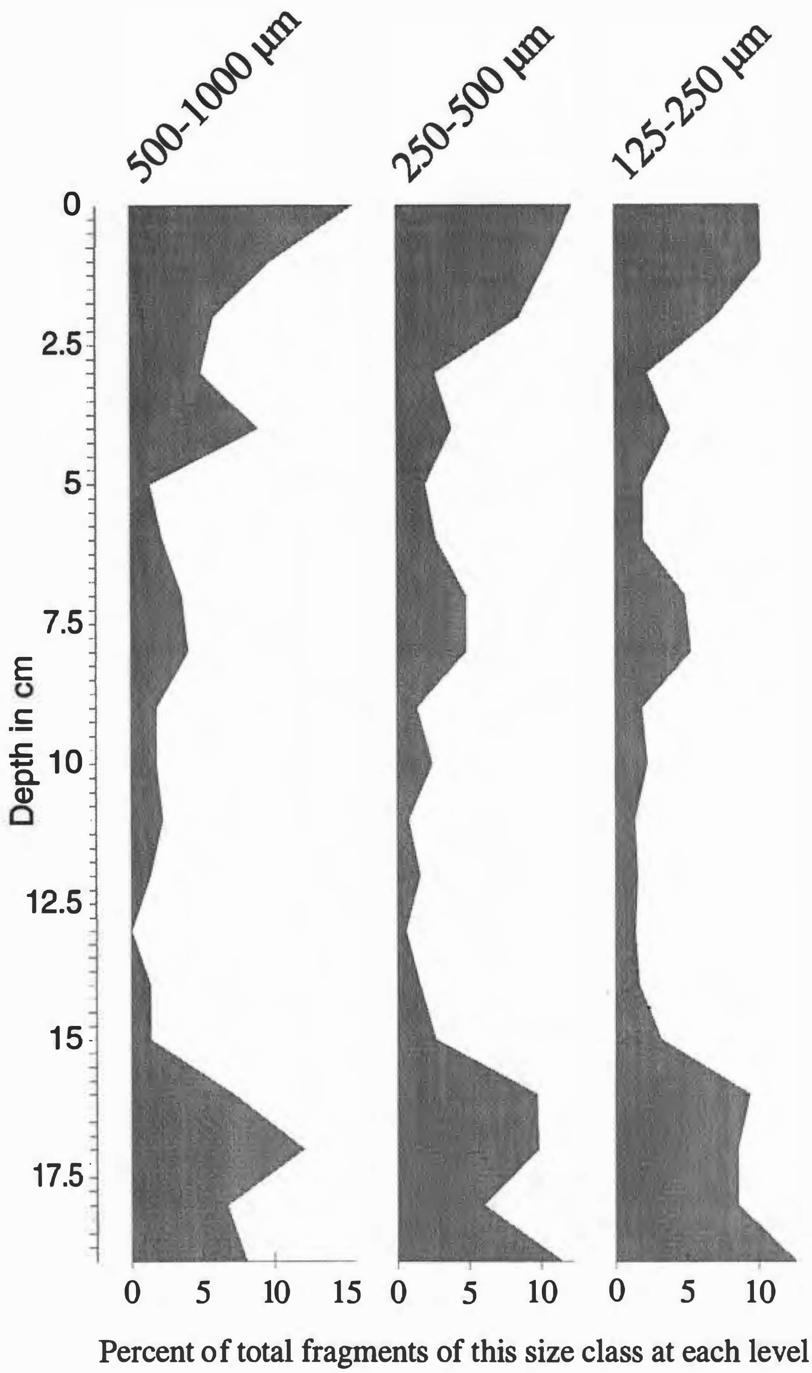

Figure 4.8 Core 190 Size Class Comparison. This figure shows the percent values for the 500–1000 µm, 250–500 µm, and 125–250 µm size classes for core 190. The curves for each size class show the percentage of charcoal in that size class at each depth, so each column sums to 100%.

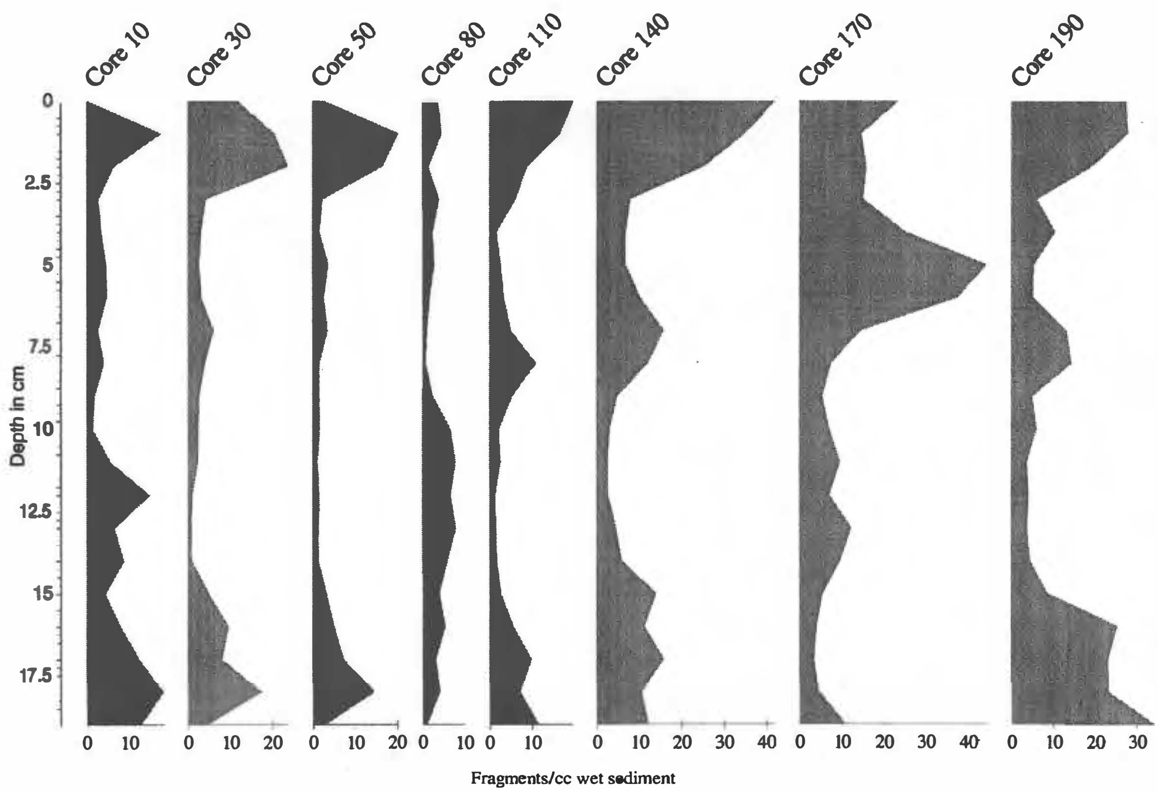

Figure 4.9 Charcoal Concentration in 125–250 µm size class at each core site.

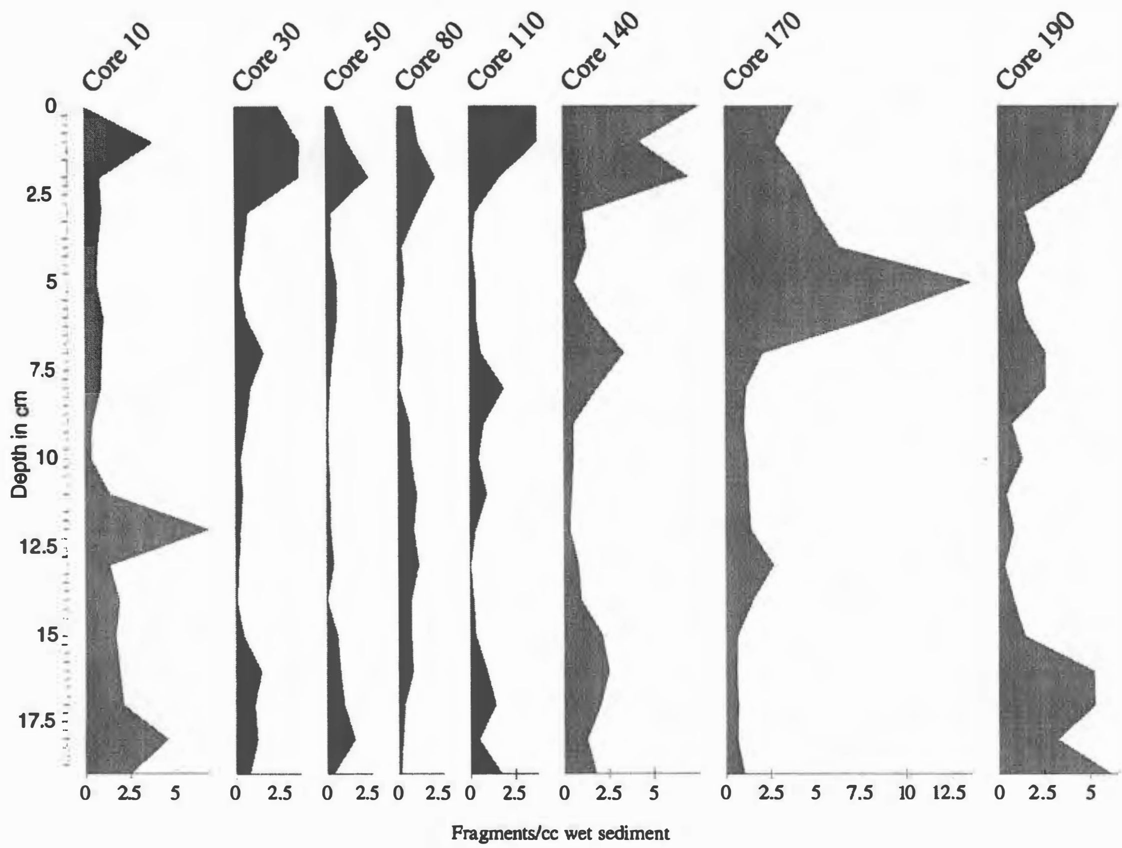

Figure 4.10 Charcoal Concentration in 250–500 μm size class at each core site.

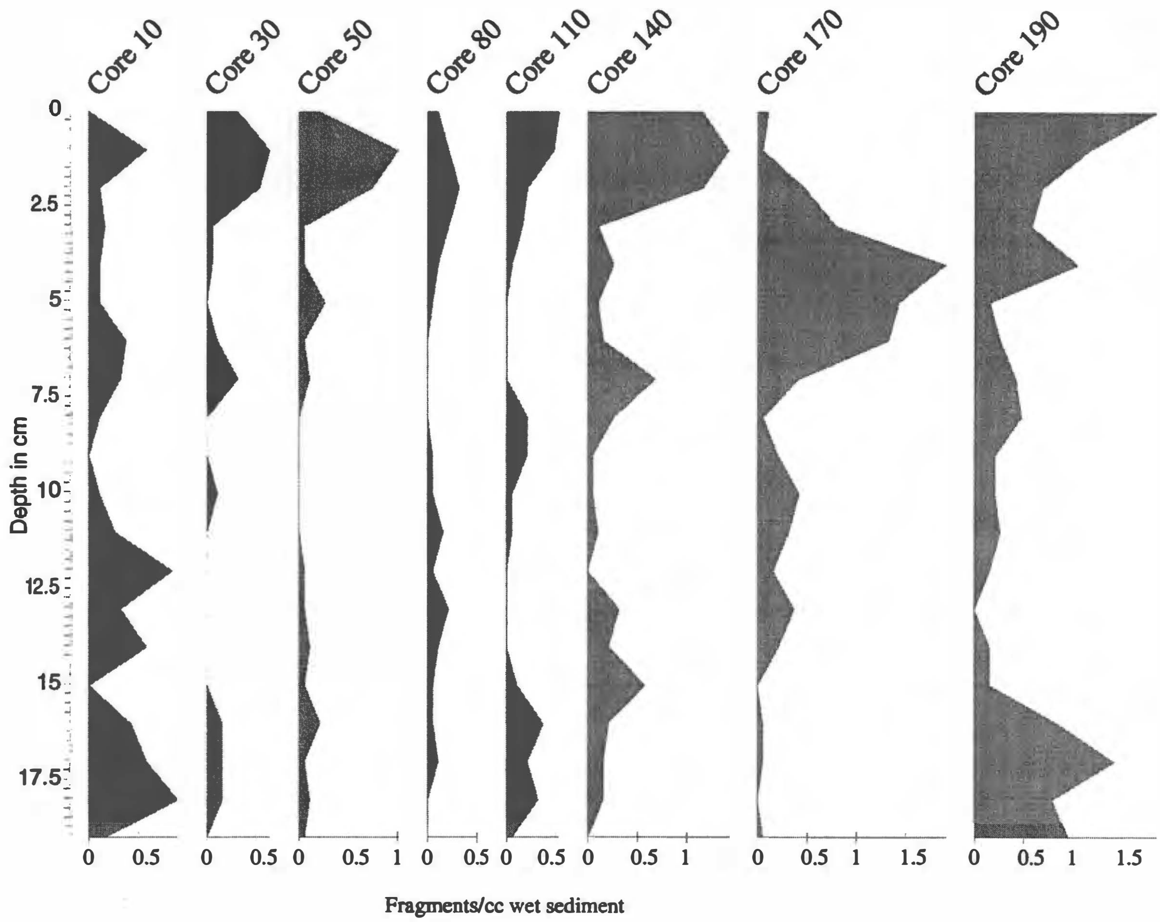

Figure 4.11 Charcoal Concentration in 500–1000 µm size class at each core site.

4.5 Total Charcoal Accumulation

Figure 4.12 shows the total accumulation of charcoal per square cm in each core. A visual inspection of this diagram suggests the general pattern of charcoal abundance across the lake. The length of the analyzed portion of each core was 20 cm.

4.6 Charcoal Influx for Core 140

The two diagrams of charcoal influx for Core 140 (Figs. 4.13 and 4.14) are based on chronologies developed using the radiocarbon date obtained by Horn (1993) at a depth of 96 cm in Morrenas-1 Core 2. Fig. 4.13 uses a constant sedimentation rate of 0.081 cm/year estimated by linear extrapolation. Fig. 4.14 makes use of an applied heuristic model developed by K. Orvis, in which the sedimentation rate varies by depth and is faster in the more watery, uppermost sediments that correspond to the sediment recovered at Core Site 140. The peaks in charcoal

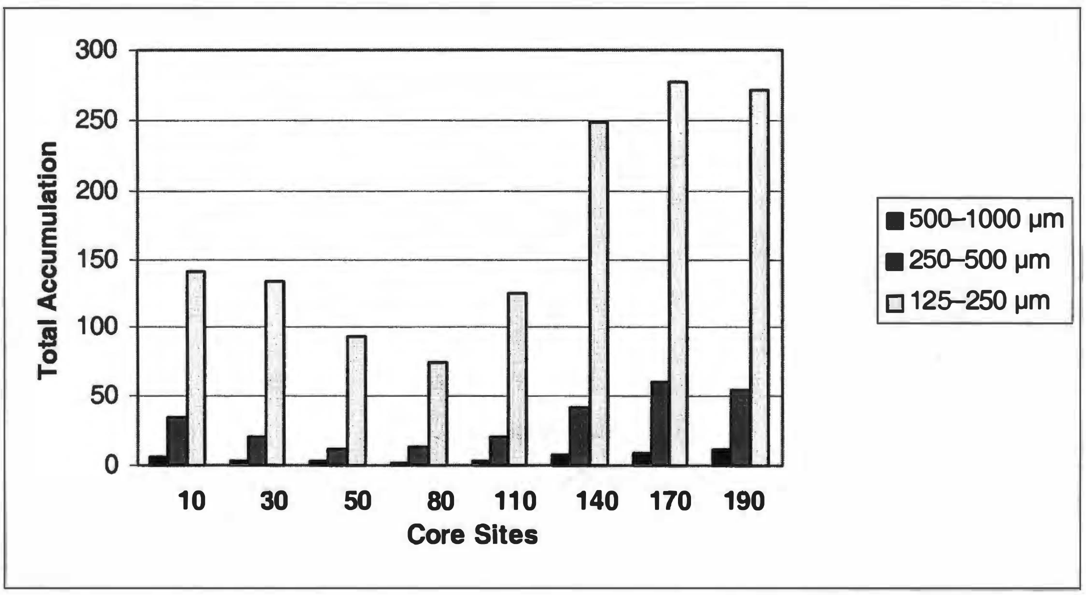

Figure 4.12 Total Accumulation of Charcoal Particles/cm^2. This figure shows the total accumulation of charcoal particles/cm^2 in each of the 20 cm long core sections analyzed. The values for each core site are the sum of the charcoal fragment counts in all levels divided by the cross sectional area of the core.

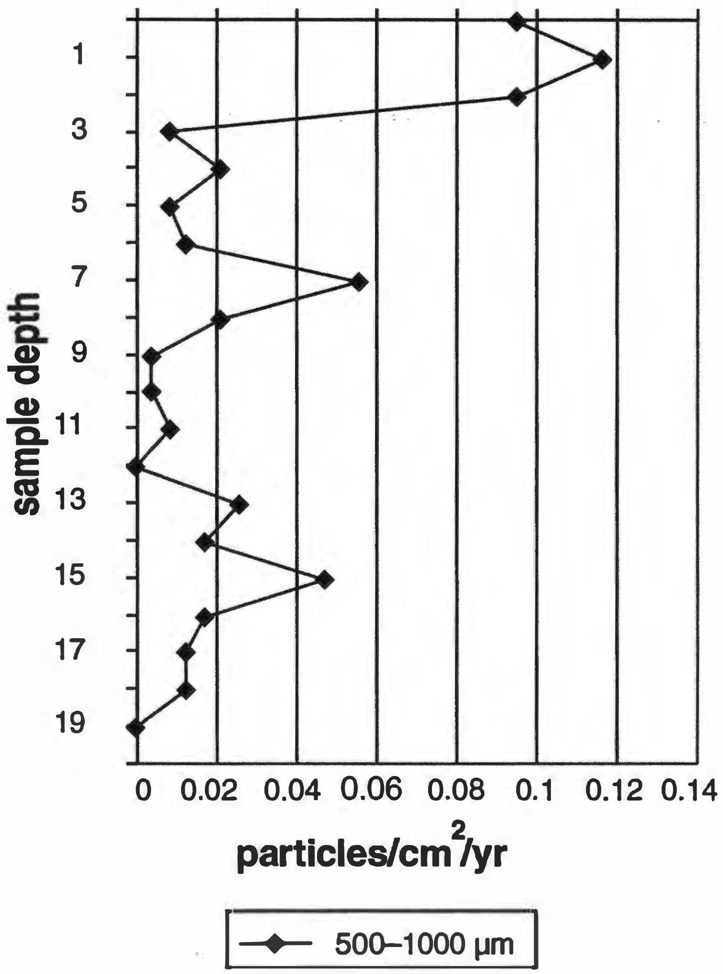

Figure 4.13 Core 140 Charcoal Influx Based on Linear Age-Depth Model.

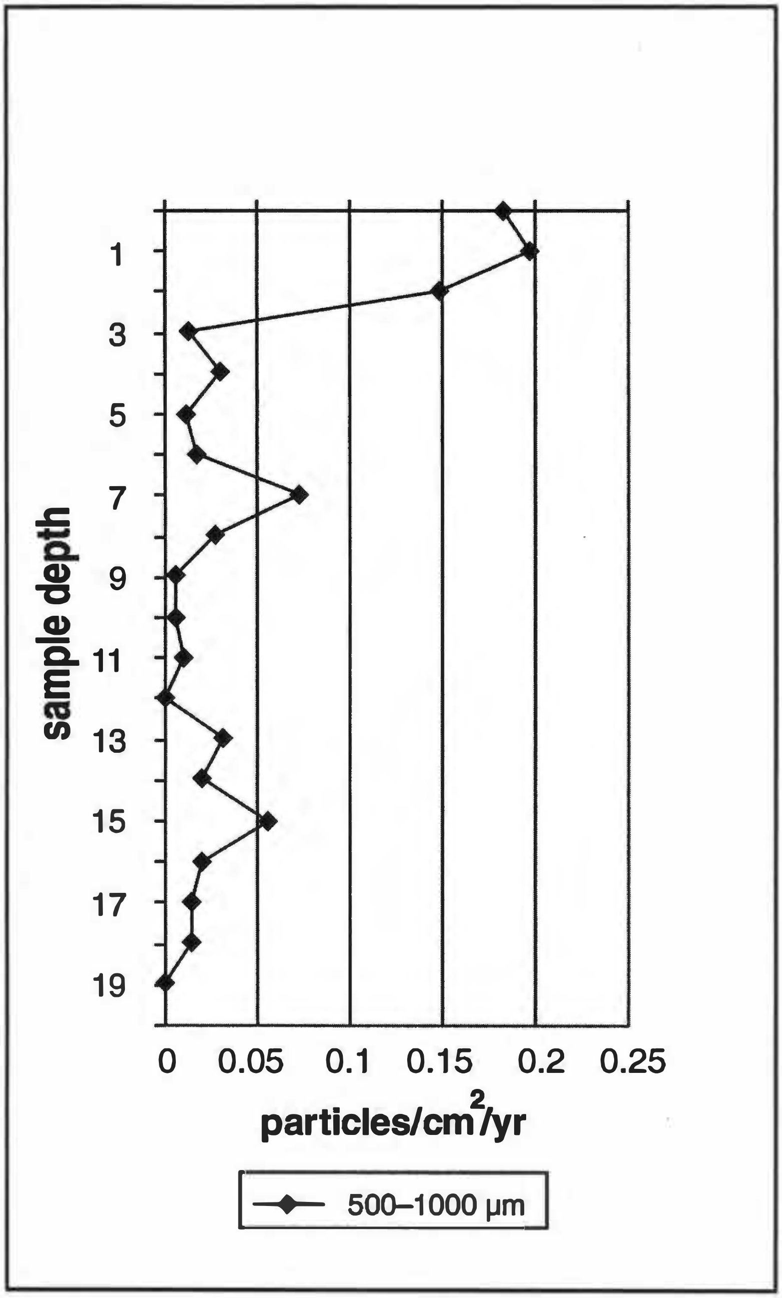

Figure 4.14 Core 140 Charcoal Influx Based on Applied Heuristic Age-Depth Model.

influx are larger when influx is calculated using these higher sedimentation rates, because each 1-cm slice of the core represents less time. I discuss these two chronologies based on the ^{14}C date and why I think that they provide better estimates of the sediment chronology than the ^{210}Pb results in the following section of this thesis.

4.7 Core 200 Charcoal Quantity

Figure 4.15 shows the charcoal stratigraphy of Core 200.

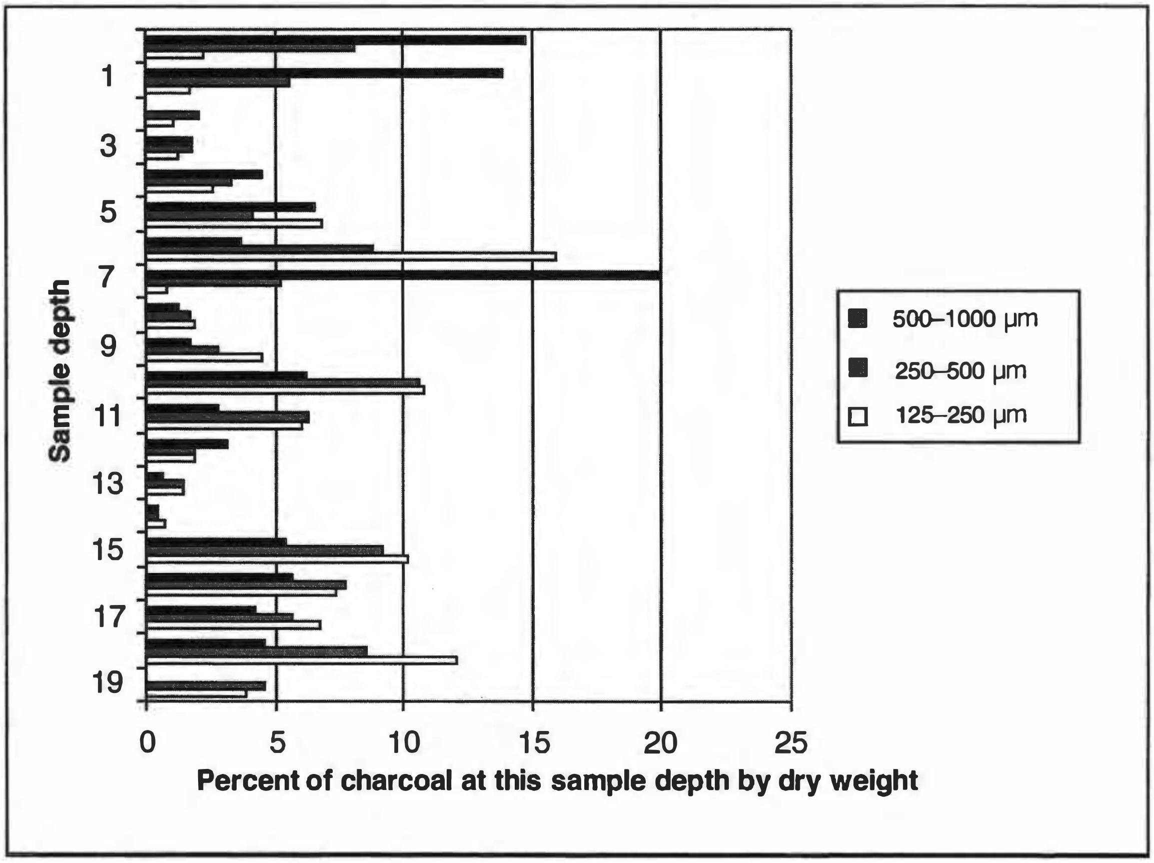

Figure 4.15 Core 200 Charcoal Quantity. Sample 0 did contain some charcoal in the 500–1000 µm size class, but the pertri dish actually weighed less after drying the sample. Each sample weighed ~1 g. Some weight differences could be caused by changes in the weight of the glassware due to loss of adsorbed water during the drying process (K. Orvis, pers. comm.)

5.0 Discussion

5.1 Introduction

At the beginning of this project, I hoped to develop evidence that would link charcoal peaks in the sediment stratigraphy to the fires that occurred in the Valle Morrenas in 1953, 1961, and 1976. Establishing a link between modern charcoal deposits and known fires requires information about how patterns of charcoal stratigraphy compare between different sediment core sites. Also, verifying the reliability of the long term charcoal record requires information about the relationships between different size classes of charcoal fragments. Finally, this analysis requires a reliable estimate of sediment age at each sample depth in the sediment stratigraphy. In this chapter, I discuss my results in light of these needs, and I discuss how this information can be used to develop better fire histories from interpretations of lake sediment charcoal stratigraphy in the Chirripó páramo.

5.2 Size Classes

For each core, visual inspection of the charcoal curves indicates that there is strong similarity between size classes (Figs. 4.1–4.8). Millspaugh and Whitlock (1995) also demonstrated that the size classes within macroscopic ranges tend to have consistent stratigraphic patterns. Some researchers (Gardner and Whitlock, 2001; Long *et al.*, 1998) have as a consequence based their research on only one size class. Their choice of size class has been based on convenience in terms of numbers and visibility of fragments to count.

The consistency between size classes demonstrated by this work suggests that limiting analysis to one size class is a valid approach. The labor-intensive nature of the laboratory analysis used for quantifying macroscopic charcoal provides further grounds for using only one size class in macroscopic charcoal analysis.

The results of this study strengthen the previous charcoal study of Morrenas Lake 1 (League and Horn, 2000) by showing that the 125–250 µm, 250–500 µm, and 500–1000 µm size classes record the same pattern. The long-term record based on particles greater than 500 µm is subject to criticism because each sample only contained a few particles, but the present study revealed that the 125–250 μm size classes consistently show the same pattern at least in the short cores analyzed here. In the 125–250 μm and 250–500 μm size classes there are large numbers of particles, so it is not likely that the pattern is random.

Clark (1988) suggested that macroscopic charcoal fragments larger than 60 μm were generally derived from local fires. Most researchers studying macroscopic charcoal have followed this to some degree by using fragments as small as 125 μm to interpret the occurrence of local fires (Millspaugh and Whitlock, 1995). However, Gardner and Whitlock (2001) did find that lake basins outside of a burned area in Oregon recorded peaks in charcoal in the 125–250 μm size class.

My results are not conclusive in this regard. If Morrenas Lake 1 recorded peaks in the smaller size classes that were not present in the larger size classes, that would argue that the smaller macroscopic charcoal can represent extra-local fires. In Morrenas Lake 1, the charcoal curves for the 125–250 μm charcoal match the charcoal curves for the 250–500 μm charcoal, so there is no evidence in the results of this study that extra-local fires have contributed macroscopic charcoal to Morrenas Lake 1. Analysis of the archived 63–125 μm charcoal may reveal evidence of fires that did not reach Morrenas Lake 1.

5.3 Within-Lake Charcoal Distribution

The three most obvious patterns of the charcoal distribution within the lake are a consistent pattern in charcoal stratigraphy among most of the cores (Figs. 4.9–4.11), higher charcoal accumulation in the littoral zone (Fig. 4.12), and evidence of sediment focusing in the deepwater area. Inferring from the patterns of charcoal distribution in Morrenas Lake 1, I believe that I see evidence of fluvial input of charcoal, sediment slumping, and movement of charcoal by wind-generated currents. In addition, the signal from charcoal deposited during a fire event is likely confounded by charcoal redeposited by several other processes, such as redeposition caused by lower lake levels (Hom and Sanford, 1992), and vertical sediment mixing caused by bioturbation and wave action (Larsen and MacDonald, 1993). However, the consistency among the charcoal curves (Figs. 4.9–4.11) suggests that most possible core sites would reveal similar patterns, and thus that charcoal records from the lake are useful for interpreting past fires.

Higher levels of charcoal concentration in the near shore sediments (Fig. 4.12) are likely a result of wind-generated currents. Wind-generated surface currents move charcoal toward the lakeshore, and long shore currents distribute charcoal around the perimeter of the lake. A similar pattern was observed in Elk Lake, Canada (Bradbury, 1996). There is no climatic data on wind direction available for Valle Morrenas, but in a small lake, the size of Morrenas Lake 1, winds from all directions are likely to have a similar effect in that the charcoal will generally accumulate in all of the near shore sediments.

Charcoal concentrations in the near shore sediments are higher on the eastern shore than the western shore (Fig. 4.12, Fig 4.15). The eastern shore core sites, Core 190 and Core 200, are closer to sources of fluvial input (Fig. 2.3). The eastern shore and northern shores are also adjacent to the valley walls of Valle de las Morrenas, whereas the rest of the lake is surrounded by lower relief (20 m) topography. This position places those core sites closer to charcoal that could be transported by overland flow (Clark, 1988).

Postfire fluvial deposition is likely. The drainage pattern in Valle Morrenas is highly deranged. In addition to the larger, permanent lakes, the valley is dotted with small intermittent ponds that interrupt streams and serve as traps for sediment, including charcoal. The landscape of the Valle Morrenas is covered with charcoal left over from the most recent fire over 25 years ago. Charcoal stored in these charcoal traps can be remobilized into streams and transported into Lake 1 during the wet season.

During the course of fieldwork, I observed portions of the bottom of the intermittently dry lake 0A, which flows into Lake 0 and then (Fig. 2.2) into Lake 1, to be covered with a thick layer (several cm) of charcoal. I also observed that the channels of the intermittent streams that drain into Lake 1 also contain areas of charcoal deposits.

A stream that flows into Lake 1 enters the lake on the southeast shore (Fig. 2.3). The core sites that are closest to this area also have the highest levels of total charcoal accumulation (Fig 4.12). This is also near the lake's deepest point. Charcoal is deposited on the south shore by currents and water, and currents from the stream may move this charcoal closer to the center of the lake. Wave action also stirs up charcoal in the littoral zone that can then be distributed to the center of the lake (Larsen and MacDonald, 1993; Bradbury, 1996).

Core 200 (Fig. 4.15) was taken from a shallow-water, near-shore core site (Fig. 2.3). The extremely high concentration of charcoal prevented analysis by charcoal counting. At the time of extrusion, this core was different from the others. Somehow, the excess water above the sediment-water interface in Core 200 had drained from the core, through the sediment and out the plug at the base. This loss of water may have occurred throughout the section, resulting in higher charcoal concentrations. Compounding this field sampling problem is the possibility that Core 200 was retrieved from an area where thick layers of charcoal have been deposited, or re-deposited recently. This type of deposition could have been caused by a combination of wave action and longshore currents (Larsen and MacDonald, 1993; Bradbury, 1996). Regardless of whether the pattern of charcoal stratigraphy in Core 200 (Fig. 4.14) affected only by the field sampling problem, or also by natural processes acting on the lake sediments, it appears that the time span of this core may not be similar to the other cores analyzed in this study.

The depth of the largest charcoal peak in Core 170 suggests sediment focusing in the deepest part of the lake (Fig. 4.9–4.11). Core 170 was retrieved from an area of deep water (Fig. 2.3). The largest and most recent charcoal peak in this core occurs at a depth of 4–5 cm, whereas the largest and most recent peak in all of the other cores occurs in the uppermost 2 cm. This suggests that the sedimentation rate is higher at this core site, possibly due to gravity induced sub-aqueous slumping. This process has been described in other lakes (Ludlam, 1973; Larsen and MacDonald, 1993).

Core 170 is close to an inlet (Fig. 2.3), so it is possible that sediment originating from fluvial input could also increase the sedimentation rate in Core 170. Currents created by fluvial input could carry sediment from the stream to this deepwater site. It is also possible that a current produced by an inflowing stream could be the mechanism that triggers sub-aqueous slumping.

5.4 Temporal Resolution

I have two lines of evidence concerning the sedimentation rate in Morrenas Lake 1: ^{210}Pb data for Core 50, obtained for this study, and radiocarbon dates for Core 2 that were obtained for a previous study (Horn, 1993). Both are problematic, but the ^{14}C dates are less so.

^{210}Pb produced in lake sediments as a decay product of ^{226}Ra is referred to as supported, while ^{210}Pb deposited in lake sediments as a decay product of Radon gas in the atmosphere is referred to as unsupported. The presence of ^{226}Ra in the Lake 1 sediments was below the minimum detectable limits of gamma-ray spectrometry. This indicates that all of the ^{210}Pb in the sediments is unsupported, or washed out from the atmosphere with rainfall.

Ideally, sediment chronologies can be developed with ^{210}Pb analysis following the example of Nittrouer *et al.* (1984). In the sediments studied by Nittrouer *et al.* (1984), the uppermost sediments were intensely mixed, and ^{210}Pb quantity was the same until the sample depth was from below the mixing layer. Below the mixing layer, the ^{210}Pb quantity decreased logarithmically with sediment age as the ^{210}Pb decayed over time, until only the supported ^{210}Pb remained. This relationship of decreasing ^{210}Pb quantity with sample depth was used to date the sediments.

In Core 50 from Lake 1, ^{210}Pb was only detected in the upper 4 cm of sediments, and the quantity is variable, rather than decreasing with sample depth. This indicates that ^{210}Pb deposition is episodic (I.L. Larsen, pers. comm.), or that the upper 4 cm of the Lake 1 sediments are mixed vertically, perhaps by bioturbation (Larsen and MacDonald, 1993). The process by which episodic input of ^{210}Pb could occur is unclear, and beyond the scope of this study. Vertical mixing of sediments could cause the observed pattern by changing the ^{210}Pb profile. The absence of ^{210}Pb below that sample depth indicates that ^{210}Pb has not been mixed any deeper than 4 cm, which is an indication that vertical mixing of sediments does not occur at depths more that 4 cm below the sediment-water interface.

Radioisotopes can generally be detected in the natural environment for 5–10 half-lives (I.L. Larsen, pers. comm.). With a half-life of 22.3 years, the absence of ^{210}Pb below 4 cm suggests that those sediments are old enough for all of the ^{210}Pb to have decayed to a level that is below the minimum detectable limit, or between 111 and 223 years old at 5 cm below the sediment surface. The sedimentation rate suggested by the ^{210}Pb evidence is 0.022–0.045 cm/yr.

This analysis is problematic for a variety of reasons. ^{210}Pb tends to bind to clay particles in lake sediments, but the Morrenas 1 lake sediments are primarily organic. The uppermost sediments are also very watery, and the volume of each 1 cm core section was fairly small (18.75 cm^3). As a result, the dry mass of each sample was very small, and the amount of ^{210}Pb was very low. It is possible that with larger sample sizes, ^{210}Pb might have been detected at deeper levels in the sediment core. For a future study, it may be possible to test the sedimentation rate suggested by the ^{210}Pb analysis using AMS ^{14}C dating of bulk sediments or charcoal from the bottoms of one or more of the cores that were retrieved for this study.

^{137}Cs was not detected in the Lake 1 sediments for many of the same reasons that ^{210}Pb was only detected in small quantities. Also, global atmospheric circulation patterns probably prevented much of the radioactive fallout from bomb testing from being deposited in low latitudes and high elevations.

The best evidence of sediment age from radioisotopes is probably the radiocarbon dates from Morrenas-1 Core 2 (Table 2.3). However, this evidence is also problematic because the analysis was done for a long-term record of pollen and charcoal, so the sampling scheme was not designed to date the uppermost sediments. In addition, the dates are from a sediment core that was not analyzed for this study. However, the core site of Core 2, which is from a deepwater site, is close to the core sites of Cores 140 and 170 m (Fig 2.3). The uppermost radiocarbon date on Core 2 provides evidence that can be considered along with the study of ^{210}Pb.

A first-order approximation of age-depth ratios in a core is usually obtained by linear interpolation between calibrated dates, or between an uppermost calibrated date and the sediment surface, whose age is the date of sampling. When sedimentation rates are fairly constant over time, and when sediment has been compacted to approximately invariant water content, such an approach works reasonably well. Very near the surface, such an approximation may be invalid because it is the very uppermost sediments that will have dewatered the least. The higher water content means that the same dry mass of accumulated sediment will occupy a greater vertical depth than it would deeper down—in other words, less elapsed time is represented by each vertical centimeter of undisturbed sediment.

Because I am discussing the uppermost few cm of sediment, the problem becomes critical for interpreting the results of this study. In order to bring attention to the issue, I estimate depths using two approximation methods. The first is linear interpolation between the surface and a radiocarbon date of 1148.5 Cal. yr BP (mean of ±2 sigma range, without rounding) in the uppermost meter of sediment from Core 2 (Table 5.1, date estimates from K. Orvis, pers. comm.). The second method uses a heuristic model of nonlinear water content near the surface in that same core (Table 5.2; date estimates from K. Orvis, pers. comm.), that was based on the observed instability and dewatering behavior of that core and a companion near-surface core, both collected by S. Horn and students in 1989.

The uppermost radiocarbon date from Morrenas-1 Core 2 (Table 2.3) was obtained on bulk sediment recovered from the uppermost meter of the profile. This section of the core consisted of watery sediment that was recovered using a plastic tube fitted with a rubber piston (Horn, 1993). The sediment was allowed to settle overnight before it was sampled by slicing the plastic tube lengthwise and removing material in 2 cm increments. Small holes were drilled in the tube to remove excess water. The settling and dewatering resulted in a shortening of the original length of the core. Back-calculating from the length of the section when first recovered, Horn estimated that the material comprising the uppermost date, which was taken from the 54–74 cm interval in the plastic tube, corresponded to an original depth (before dewatering) of 81–111 cm.

Table 5.1 Linear Age-Depth Model. This model is used for estimating ages from depths, based on the Morrenas-1 core site 2 PTC core, applied to Core 140. These models refer to depths in the sediment immediately after coring. This model was created by Ken Orvis based on a calibrated date of 1148.5 cal. yr. BP (mean of ±2 sigma, without rounding) centered at 64 cm in the 106 cm (shortened and dried) core.

Depth (cm)	Age (yrs)	Date AD	Date BP
0	0.0	1998	-48
1	12.3	1986	-36
2	24.6	1973	-23
3	36.9	1961	-11
4	49.2	1949	1
5	61.5	1937	13
6	73.8	1924	26
7	86.0	1912	38
8	98.3	1900	50
9	110.6	1887	63
10	122.9	1875	75
11	135.2	1863	87
12	147.5	1850	100
13	159.8	1838	112
14	172.1	1826	124
15	184.4	1814	136
16	196.7	1801	149
17	209.0	1789	161
18	221.3	1777	173
19	233.6	1764	186

Table 5.2 Applied Heuristic Age-Depth Model. This model is used for estimating ages from depths, assuming strongly nonlinear moisture content. This model is to be used for estimating ages from depths, based on the Morrenas-1 core site 2 PTC core, applied to Core 140. These models refer to depths in the sediment immediately after coring. This model was created by Ken Orvis based on a calibrated date of 1148.5 cal. yr. BP (mean of ±2 sigma, without rounding) centered at 64 cm in the 106 cm (shortened and dried) plastic tube core.

Depth (cm)	Age (yrs)	Date AD	Date BP
0	0.0	1998	-48
1	6.4	1992	-42
2	13.6	1984	-34
3	21.5	1977	-27
4	29.7	1968	-18
5	38.3	1960	-10
6	47.1	1951	-1
7	56.2	1942	8
8	65.0	1932	18
9	75.0	1923	27
10	84.6	1913	37
11	94.4	1904	46
12	104.3	1894	56
13	114.4	1884	66
14	124.5	1873	77
15	134.8	1863	87
16	145.2	1853	97
17	155.7	1842	108
18	166.2	1832	118
19	176.9	1821	129

It should be noted that this adjustment was made with the simplifying assumption that the amount of settling was equivalent for all depth intervals recovered, when in fact the uppermost sediments (being the most watery) most likely settled the most. As a result, the adjusted depth of 81–111 cm probably overestimates the true equivalent depth of the section, and hence may also overestimate the rate of sediment accumulation (S. Horn, pers. comm.).

Keeping that possibility in mind, we can use the uppermost radiocarbon date with caution to provide an estimate for the age of the sediments studied in this project. The uppermost radiocarbon date of 1230±170 yr calibrates to 1510–790 cal. yr BP (±2 sigma, rounded) using version 4.3 of the CALIB radiocarbon calibration program (Stuiver and Reimer, 1993; see also Table 2.3). The midpoint of the unrounded calibrated range is 1148.5 cal. yr BP. The upper sediment surface should be equivalent to 1989 AD (when the core was recovered), which is equivalent to –39 BP (since BP = before 1950). Applying the calibrated date to the midpoint of the interval dated (96 cm) yields a sedimentation rate of 96 cm in 1187.5 calibrated years, or 0.081 cm/yr.

In the second model, a heuristic model of nonlinear water content, the sediment is assumed to have a constant background water content that is not apt to drain away, which is estimated here at 89.5% by weight (K. Orvis, pers. comm.). This is somewhat analogous to the field capacity of a terrestrial soil. In addition, there is "excess" water that diminished rapidly and then more gradually with increasing depth.

Excess water was estimated for the 1989 near-surface core using the formula

$$W = (10 - \ln(d - 1)) \times 0.7745$$

...where W is the weight of excess water, and d is depth in cm. Using the same radiocarbon date and assuming a constant accumulation rate of sediment dry mass, the model yields notably different age-depth results especially near the sediment-water interface (Table 5.2). This is, admittedly, only a rough estimate of the effect of increasing near-surface water content on assigned ages, but the contrast between the results of the two approximation methods serves to illustrate the potential for error.

5.5 Synthesis of Sediment Chronology with Historical Evidence of Fires

A comparison of both age-depth models to the historical record of fires in Valle Morrenas in the 20th century reveals that the applied heuristic model is a better fit with my expectations. Historical evidence (Hom, 1990a and pers. comm.) indicates that the most recent fires to bum the Lake 1 watershed occurred in 1953, 1961, and 1976. My results (Figs, 4.1–4.11) show a peak in the upper 3 cm, samples 0–1 cm, 1–2 cm, and 2–3 cm. According to the linear model, this would mean that the 1953, 1961, and 1976 fires all form one compound peak in the upper sediments. With this explanation, the temporal resolution of the charcoal record would be no better than the amount of time represented by the upper 3 cm, or about 37 years (Table 5.1).

According to the applied heuristic model, the upper 3 cm samples only represent the time period since 1977, therefore the 1976 fire produced the charcoal peak in the upper 3 cm. If the explanation offered by this model were sufficient, I would expect the charcoal peak in the upper 3 cm to be followed by peaks at lower sample depths corresponding to the 1953 and 1961 fires. There is a smaller charcoal peak at 7–8 cm (1932–1942 based on the applied heuristic model) that could be the result of a fire event. Another smaller peak occurs at a sample depth too deep to be linked to either the 1953 or 1961 fire.

The peak at 7–8 cm could be a compound peak formed by the 1953 and 1961 fires, although the peak at 7–8 cm sample depth is ~2 cm too deep to be from the 1953 and 1961 fires according to the applied heuristic model. However, since this model is a rough estimate, the pattern matches reasonably well.

Also, the 1953 and 1962 fires occurred within a time span of less than 10 years. Since charcoal from the 1976 fire remains on the landscape more than 25 years later, and each sample in the uppermost sediments probably represents a time span of less than 10 years, I would expect these fires to form a single peak in the stratigraphic record, according to the applied heuristic model.

The temporal resolution, or the amount of time following a fire that must pass before a new fire event will contribute to a separate, distinguishable peak in the charcoal record, appears to depend on the amount of charcoal produced by any particular fire. The record of modern charcoal suggests that fires occurring 8 years apart or less, such as the fires in 1953 and 1961, are likely to contribute to the same charcoal peak in the stratigraphic record. Fires occurring at least 15 years apart, such as the fires occurring in 1961 and 1976, may contribute to separate, distinguishable peaks. However, a large amount of charcoal was deposited into the lake sediments of Morrenas Lake 1 between 15 and 22 years after the 1976 fire, so much so that if a fire had burned Valle Morrenas between 1992 and 1998, it would likely have contributed to the same charcoal peak as the 1976 fire.

5.6 Application of Temporal Resolution Information to the Long-Term Charcoal Record

Previously, League and Horn (2000) reported, based on the long term Morrenas Lake 1 charcoal record, that fires have burned in the Valle Morrenas at intervals throughout the Holocene. It may be possible to use the information about temporal resolution and charcoal background levels to conduct a more detailed analysis of the long term record of Lake 1 by applying the record of modern charcoal influx to the record that extends throughout the Holocene.

The charcoal influx based on the applied heuristic age-depth model (Fig. 4.14) indicates that the 1976 fire produced a peak of more than 0.2 particles/cm^2/yr. Peaks at least this large in the long term record likely represent a fire or a series of fires occurring in a time span that is less than the temporal resolution for the amount of charcoal produced in those fires. There are 8 peaks in the long-term record (Fig. 5.1) that are greater than 0.2 particles/cm^2/yr.

According to the influx based on the applied heuristic age-depth model, the peak at 7–8 cm in Core 140 that I believe corresponds to the 1953 and 1961 fires combined produced a peak of 0.073 particles/cm^2/yr. Influx peaks as high as 0.073 probably also indicate a fire or series of

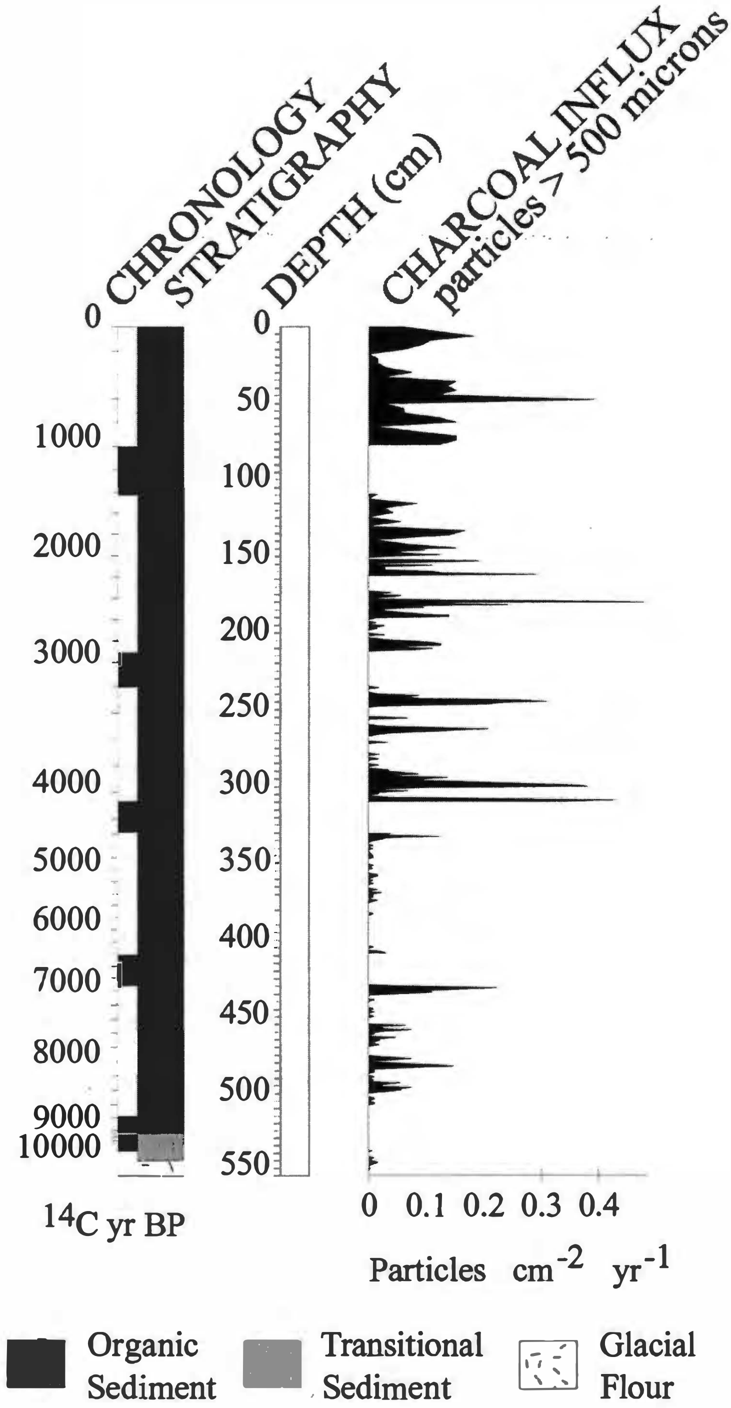

Figure 5.1 Long-term Lake 1 Charcoal Record. This figure was adapted from League and Horn, (2000). The black bars on the left correspond to areas where bulk sediment was removed for radiocarbon dates.

fires, however, it is possible that fires could produce an influx that is smaller. For the long-term record, there are 28 peaks that exceed 0.073 particles/cm^2/year. Interestingly, during the period between 5000 and 7000 years BP, there are no peaks in influx greater than 0.073 particles/cm^2/year.

The long-term charcoal record (Fig. 5.1) appears to match records of past climate from other parts of the circum-Caribbean (Hodell *et al.*, 1995; Haug *et al.*, 2001). Stratigraphic records of terragenic metals in marine sediments from the Cariaco Basin, north of Venezuela (Haug *et al.*, 2001), provide a precipitation record for northern South America during the Holocene. This record indicates that precipitation increased in the Orinoco Basin during the Holocene thermal maximum (7000 BP), and that precipitation has decreased steadily since then.

Haug *et al.* (2001) argued that Milankovitch forcing caused decreased seasonality of insolation in the northern hemisphere, and increased seasonality of insolation in the southern hemisphere during the late Holocene. This caused the ITCZ to migrate southward since the Holocene thermal maximum. Climate records from various sites worldwide support this interpretation (Haug *et al.*, 2001).

The long-term charcoal record from Lake 1 also supports this interpretation because wetter conditions in the páramo would reduce the likelihood of fire. In the treeless Chirripó páramo, less frequent fire would result in less charcoal production, because the absence of fire for long periods does not necessarily result in a large fuel build up, as in other areas.

Charcoal input to Lake 1 sediments increased during the late Holocene, with low charcoal concentrations in the sediments that were deposited during the Holocene thermal maximum, ~6800–4200 ^{14}C y BP (Fig 5.1). The long term record suggests a wetter period during the early to mid-Holocene. Records from the Yucatan also suggest a wetter period during the mid-Holocene (Hodell *et al.*, 1995).

Sediment records from the Cariaco Basin core site at 10° N latitude may show trends that would be broadly representative of climate patterns during the Holocene for the Chirripó páramo (9.5° N) in regards to the position of the ITCZ. In the scenario described by Haug *et al.* (2001), during the Holocene thermal maximum, the ITCZ would be closer to the Chirripó páramo for longer periods of time each year, resulting in a longer wet season. These conditions would decrease the likelihood of fire in the Chirripó páramo.

Conclusions

Fire history studies are more useful when they provide indications of fire regime characteristics such as fire frequency, intensity, and area burned. This type of information can be used in conjunction with proxy records to learn about a wide variety of topics that concern geographers such as climate change, vegetation dynamics and human settlement patterns. This study does not go this far, but it is an improvement over the previous status of fire history in the Chirripó páramo, and it is one of the few detailed studies of charcoal distribution in lake sediments. Specifically, this research provides information about size classes and the within-lake distribution of charcoal. It also provides some information about the temporal resolution of the charcoal record that can be used to better interpret the long-term record.

The analysis described in this thesis demonstrates that it is reasonable to expect that the patterns shown in the long charcoal record based on the 500–1000 µm charcoal size class would have been evident for smaller size classes of charcoal had they been analyzed. This finding is important because the long-term record of charcoal that extends throughout the Holocene is based on particles greater than 500 µm, and many samples in that record had very low numbers of fragments. The indication that there is a similar pattern in smaller size classes, where the numbers of fragments are much greater, makes the long term record less subject to criticism.

The indication that different size classes produce the same pattern suggests that methods that are simple and quick are suitable for the long term studies of charcoal. Basing the record on one size class following League and Horn (2000) and Gardner and Whitlock (2001) is appropriate.

Patterns of charcoal distribution suggest that the most active depositional and taphonomic processes are related to wind generated currents and fluvial deposition. There is more charcoal in the nearshore sediments, probably due to wind generated currents, and there is more charcoal on the east side of the lake, probably due to its closer proximity to the valley wall and an inlet. My results also indicate that the general pattern of charcoal stratigraphy is consistent among core sites throughout the lake. This suggests that applying the analysis of a core from Morrenas Lake 1 to another core from Morrenas Lake 1 is a valid approach .

I made attempts to improve the sediment chronology with analysis of ^{137}Cs and ^{210}Pb. While some information was obtained about the amount of ^{210}Pb in the Morrenas Lake 1 sediments, the analysis was problematic due to the very low amounts of ^{210}Pb, and I could not develop a reliable age-depth model based on the ^{210}Pb.

In spite of their limitations for this study, low-energy radioisotopes remain a powerful tool for analyzing sediment chronology, and they should be used to develop temporal interpretation models that can be applied to long term records. An ideal research design in the future would include a method to simply and quickly produce a long-term record of charcoal with contiguous sampling, and a detailed study of radioisotopes in near-surface sediments.

Sampling with a large-diameter near surface corer, as described by Fisher *et al.* (1992), could help to overcome some of the limitations of ^{210}Pb dating with very watery, organic sediments. It would be more likely to detect ^{210}Pb at lower sample depths with larger sample sizes, and detecting ^{210}Pb at lower sample depths could make it possible to construct a reliable age-depth model following Nittrouer *et al.* (1984).

The analysis in this study made some improvements in knowledge of the temporal resolution of fire histories based on sediments from Morrenas Lake 1. This study presents a possible temporal resolution and background level for interpreting the long term record of charcoal in Morrenas Lake 1. It may be possible to use this information to conduct a more detailed statistical analysis as described by Mohr et al. (1998), Long et al. (2000), and Brunelle and Andersen (2003). The long macroscopic charcoal record of Lake 1 may also indirectly record a signal of precipitation trends during the Holocene that complements other studies of lake and marine sediments in the neotropics.

References

Bauer, R., Orvis, K., and Edlund, E. (1991). CalPalyn's instruction file, version 2.1. Palynology and Paleobotany Laboratory, University of California, Berkeley.

Bennet, K.D. (1986). Coherent slumping of early postglacial lake sediments at Hall Lake, Ontario, Canada. *Boreas* 15: 209–215.

Blackford, J.J. (2000). Charcoal fragments in surface samples following a fire and the implications for interpretation of subfossil charcoal data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164: 33–42.

Bradbury, J.P. (1996). Charcoal deposition and redeposition in Elk Lake, Minnesota, USA. *The Holocene* 6: 339–344.

Brunelle, A., and Anderson, R.S. (2003). Sedimentary charcoal as an indicator of late-Holocene drought in the Sierra Nevada, California, and its relevance to the future. *The Holocene* 13(1): 21–28.

Carcaillet, C., Bouvier, M., Fréchette, B., Larouche, A.C., and Richard, P.J.H. (2001). Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. *The Holocene* 11: 467–476.

Clark, J.S. (1988). Particle motion and theory of charcoal analysis: source area, transport, deposition, and sampling. *Quaternary Research* 30: 67–80.

Clark, J.S. (1990). Fire and climate change during the last 750 yr in northwestern Minnesota. *Ecological Monographs* 60: 135–159.

Clark, J.S., and Royall, P.D. (1994). Pre-industrial particulate emissions and carbon sequestration from biomass burning in North America. *Biogeochemistry* 24(1): 35–51.

Clark, J.S., Royall, P.D., and Chumbley, C. (1996). The role of fire during climate change in an eastern deciduous forest at Devil's Bathtub, New York. *Ecology* 77(7): 2148–2166.

Clark, J.S., Lynch, J., Stocks, B.J., and Goldammer, J.G. (1998). Relationships between charcoal particles in air and sediments in west-central Siberia. *The Holocene* 8(1): 19–29.

Clark, R.L. (1983). Fire History from Fossil Charcoal in Lake and Swamp Sediments. Ph.D. Thesis, Australian National University, Canberra.

Clark, R.L. (1984). Effects on charcoal of pollen preparation procedures. *Pollen et Spores* 26(3-4): 559–576.

Cleef, A.M., and Chaverri, A. (1991). Phytogeography of the páramo flora of Cordillera de Talamanca, Costa Rica. Pp. 45–60 in *Páramo: An Andean Ecosystem Under Human Influence.* Edited by Baslev, H., and Luyten, J.L. Academic Press, London.

Curtis, J.H., Hodell, D.A., and Brenner, M. (1996). Climate variability on the Yucatan peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. *Quaternary Research* 46: 37–47.

Cutshall, N.H., Larsen, I.L., and Olsen, C.R. (1983). Direct analysis of ^{210}Pb in sediment samples–self-absorption corrections. *Nuclear Instruments and Methods in Physics Research* 206(1-2): 309–312.

Davis, R.B. (1974). Stratigraphic effects of tubificids in profundal lake sediments. *Limnology and Oceanography* 19: 466–487.

Fisher, M.M., Brenner, M., and Reddy, K.R. (1992). A simple, inexpensive piston corer for collecting undisturbed sediment/water interface profiles. *Journal of Paleolimnology* 7: 157–161.

Fjeldså, J. (1991). Biogeography of the birds of the *Polylepis* woodlands of the Andes. Pp. 31–44 in *Páramo: An Andean Ecosystem Under Human Influence.* Edited by Baslev, H., and Luyten, J.L. Academic Press, London.

Gardner, J., and Whitlock, C. (2001). Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *The Holocene* 11: 541–549.

Haberyan, K.A., and Hom, S.P. (1999). A 10,000 year diatom record from a glacial lake in Costa Rica. *Mountain Research and Development* 19: 63–70.

Hastenrath, S. (1973). On the Pleistocene glaciation of the Cordillera de Talamanca, Costa Rica. *Zeitschrift für Gletscherkunde und Glazialgeologie* 9: 105–121.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., and Röhl, U. (2001). Southward migration of the intertropical convergence zone throughout the Holocene. *Science* 293: 1304–1308.

Hellström, B. (1941). Wind effect on lakes and rivers. *Ingen Vetensk Ak. Handl.* 158: 191.

Hilton, J. (1985). A conceptual framework for predicting the occurrence of sediment focusing and sediment redistribution in small lakes. *Limnology and Oceanography* 30: 1131–1143.

Hodell, D.A., Curtis, J.H., and Brenner, M. (1995). Possible role of climate in the collapse of classic Maya civilization. *Nature* 375: 391–394.

Horn, S.P. (1986). Fire and Páramo Vegetation in the Cordillera de Talamanca, Costa Rica. Ph.D. Thesis. University of California, Berkeley.

Horn, S.P. (1989). Postfire vegetation development in the Costa Rican páramos. *Madroño* 36(2): 93–114.

Horn, S.P. (1990a). Vegetation recovery after the 1976 páramo fire in Chirripó National Park, Costa Rica. *Revista de Biología Tropical* 38(2): 267–275.

Hom, S.P. (1990b). Timing of deglaciation in the Cordillera de Talamanca, Costa Rica. *Climate Research* 1: 81–83.

Horn, S.P. (1993). Postglacial vegetation and fire history in the Chirripó páramo of Costa Rica. *Quaternary Research* 40: 107–116.

Horn, S.P. (In press). Vegetation dynamics following recent fires in the Buenavista and Chirripó páramos of Costa Rica. Chapter in *Los Páramos de Costa Rica*, edited by M. Kapelle, S. Horn, and Chaverri, A. INBIO Press, Santo Domingo, Costa Rica.

Horn, S.P., and Sanford, R.L. (1992). Holocene fires in Costa Rica. *Biotropica* 24(3): 354–361.

Horn, S.P., and League, B.L. (in press). Lake sediment records of Holocene vegetation and fire history in the Chirripó páramo of Costa Rica. Chapter in *Los Páramos de Costa Rica*, edited by M. Kappelle, S. Horn, and Chaverri, A. INBIO Press, Santo Domingo, Costa Rica.

Iversen, J. (1941). Land occupation in Denmark's Stone Age. *Danmarks Geologiske Undersøgelse* Series 2, no. 66, 68 pp.

Lane, C. Horn, S.P., and Mora, C.I. (2002). Paleoecological significance of stable carbon isotopes in lake sediments from the Chirripó páramo of Costa Rica (abstract). *Geological Society of America Abstracts with Programs* 34.

Lane, C. (2003). The Paleoecological Significance of Stable Carbon isotopes in Lake Sediments from the Chirripó Páramo of Costa Rica. M.S. thesis, Department of Geography, University of Tennessee.

Larsen, C.P.S., and MacDonald, G.M. (1993). Lake morphometry, sediment mixing and the selection of sites for fine-resolution palaeoecological studies. *Quaternary Science Reviews* 12: 781–792.

League, B.L. (1998). Sedimentary Charcoal, Magnetic Susceptibility, and Páramo Fires in Chirripó National Park, Costa Rica. Senior Honors Thesis, Department of Geography, University of Tennessee.

League, B.L., and Horn, S.P. (2000). A 10,000 year record of páramo fires in Costa Rica. *The Journal of Tropical Ecology* 16: 747–752.

Long, C.J., Whitlock, C., Bartlein, P.J., and Millspaugh, S.H. (1998). A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forestry* 28: 774–787.

Luyten, J.L. (1991). Paramos: why study them? Pp. 1–14 in *Páramo: An Andean Ecosystem Under Human Influence*. Edited by Baslev, H., and Luyten, J.L. Academic Press, London.

Ludlam, S.D. (1974). Fayetteville Green Lake, New York, 6, The role of turbidity currents in lake sedimentation. *Limnology and Oceanography* 19: 656–664.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M., and Moser, K.A. (1991). The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Reviews* 10: 53–71.

Millspaugh, S.H., and Whitlock, C. (1995). A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. *The Holocene* 5: 283–292.

Mohr, J.A., Whitlock, C., and Skinner, C.N. (2000). Postglacial vegetation and fire history, eastern

Klamath Mountains, California, USA. *The Holocene* 10(4): 587–601.

Mortimer, C.H. (1952). Water movements in lakes during summer stratification: Evidence from the distribution of temperature in Windermere. *Proceedings of the Royal Society of London (Series B)* 265: 355–404.

Nittrouer, C.A., DeMaster, D.J., McKee, B.A., Cutshall, N.H., and Larsen, I.L. (1984). The effect of sediment mixing on ^{210}Pb accumulation rates for the Washington Continental Shelf. *Marine Geology* 54(3–4): 201–221.

Orvis, K.H., and Horn, S.P. (2000). Quaternary glaciers and climate on Cerro Chirripó, Costa Rica. *Quaternary Research* 54: 24–37.

Patterson, W.A. III, Edwards, K.J., and MacGuire, D.J. (1987). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6: 3–23.

Pitkänen, A., Lehtonen, H., and Huttunen, P. (1999). Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. *The Holocene* 9: 559–567.

Rhodes, A. N. (1998). A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. *The Holocene* 8: 113–117.

Robbins, J. A. (1982). Stratigraphic and dynamic effects of sediment reworking by Great Lakes zoobenthos. *Hydrobiologia* 92: 6116–22.

Stuiver, M., Reimer, P.J. (1993). Extended ^{14}C database and revised Calib 3.0 ^{14}C age calibration program. *Radiocarbon* 35(1): 215–230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, B., Kromer, G., McCormac, G., van der Plicht, J., and Spurk, M. (1998). IntCal98 radiocarbon age calibration, 24,000–0 BP. *Radiocarbon* 40: 1041–1083.

Wetzel, R.G. (1983). *Limnology*. CBS College Publishing, New York.

Whitlock, C., and Millspaugh, S.H. (1996). Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6: 7–15.

Wright, H.E., Jr., Mann, D.H., and Glaser, P.H. (1984). Piston corers for peat and lake sediments. *Ecology* 65(2): 657–659.

Appendices

Appendix A

Processing Protocol for charcoal sieving

1. Open the plastic bag in which the sample is stored.
2. Gently scrape the sample into a 50 ml polypropylene test tube.
3. Fill the test tube with 10% KOH and stir gently.
4. Place the test tube in a hot water bath for 1 hour.
5. Swirl the sample and wash with distilled water through nested sieves of 63, 125, 250, 500 and 1000 µm.
6. Gently wash the sample through the sieves until only charcoal remains on the sieves.
7. Wash charcoal into petri dish, dry overnight, and store for future analysis.

Appendix B

Processing protocol for KOH experiment

1. Gently crush the campfire charcoal with a mortar and pestle.

2. Place the charcoal sample in a pre-weighed petri dish.

3. Weigh the sample.

3. Place the charcoal into a 50 ml polypropylene test tube.

4. Fill the test tube with KOH (both 5% and 10% concentrations were used in the experiment).

5. Place the test tube in a hot water bath (samples were heated for either 10, 30 or 60 minutes).

6. Swirl the sample and wash with distilled water through nested sieves of 1000, 500, 250, 125, and 63 micrometers.

7. Wash the sample from each sieve into a petri dish.

8. Dry the sample at 100° C overnight.

9. Place the samples in a dessicator to cool.

10. Remove the samples from the dessicator and wrap in cellophane.

11. Unwrap the samples from the cellophane and weigh.

Vita

Brandon L. League was born in Knoxville, TN on August 27, 1976. He graduated from Powell High School, Powell, TN in 1994. Brandon received his Bachelor of Arts degree from the University of Tennessee in 1998, graduating cum Laude with a major in Geography. He developed an interest in tropical paleoecology while participating in research through the National Science Foundation's Research Experience for Undergraduates Program. Brandon entered the graduate program in geography at the University of Tennessee in 1998 with a desire to continue the research project on the fire history of Chirripó páramo that he began as an undergraduate.

Brandon's other interests include information systems, geographic and other. He is currently the interim Geospatial Applications Administrator for the National Biological Information Infrastructure's Southern Appalachian Information Node. He has accepted an offer to continue working in this capacity, and after graduation, he plans to settle down in the Knoxville area with his expectant wife, Kelly, and their two children.